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NASA Technical Paper 2147

The NASA Geodynamics Program: An Overview

Geodynamics Program Office

*Office of Space Science and Applications
Washington, DC 20546*

1983



National
Aeronautics and
Space
Administration

**Scientific and Technical
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FOREWORD

The study of the solid earth and its gravity and magnetic fields has advanced significantly in the past 20 years. This advancement has been greatly assisted by the emergence of methods which use space and space-derived technology for observations of the earth unattainable by other means.

During this period, the NASA role in solid earth studies has evolved from that of developer of new technologies into a major partnership role at Federal and International levels in the pursuance of a broad program of global geodynamics. Often progress has been rapid; new results have emerged as the technology was refined and plans have been revised to take advantage of the new capability to meet science needs.

Much of the NASA activity has been documented in program plans, in program annual reports, in newsletters, during annual program conferences, and in other information sources.

This NASA Geodynamics Program overview collectively examines the history, scientific basis, status, and results of the NASA Program and outlines plans for the next five to eight years. It is intended as an informative, non-technical, discussion of geodynamics research. It was prepared for NASA by the Science Systems Staff of the OAO Corporation.

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SECTION 1. INTRODUCTION

This document provides an overview of the NASA Geodynamics Program. The basis and objectives of the Program, formulated over a decade ago, were delineated in an early Program document entitled Application of Space Technology to Crustal Dynamics and Earthquake Research. Since that time, the Program plans and activities have matured and expanded with the knowledge gained from the testing and refining of the techniques essential to utilizing space technology for the study of geodynamics.

The initial activities of the Program are now well underway and the results to date have advanced the science of global geodynamics from the theoretical to the observational stage. Participation in the Program has grown to include investigators from a variety of federal agencies, universities and academic institutions representing twenty-five countries. Other scientific groups have indicated an interest in participating in this program, which is proving to be a pioneer of the frontiers of earth science. Due largely to its earlier successes, these activities are now projected to continue through the next decade. Moreover, the progress made since the Application of Space Technology to Crustal Dynamics and Earthquake Research was written indicates the need for a new document which details these advances.

This document was written not only to reflect upon these recent advances, but to present them in a format that includes the historical perspective, the scientific basis, and the future directions of the Program.

1.1 THE NASA GEODYNAMICS PROGRAM

The NASA Geodynamics Program was originally structured to support the Earthquake Hazard Reduction Act of 1977. This Act called for federal agency collaboration in research activities to further the understanding of the processes responsible for causing earthquakes, with the ultimate goal of predicting and therefore alleviating the dangers associated with this phenomenon. The NASA Geodynamics Program includes: 1) measuring and modeling studies which apply very long baseline interferometry (VLBI) and laser ranging data to analyze the dynamic motions of the Earth; 2) a global satellite laser network which provides information for these studies; 3) satellite missions such as Magsat and the Geopotential Research Mission (GRM); and 4) research studies advancing the techniques used to measure and analyze geodynamic phenomena. The Crustal Dynamics Project, established in 1979, comprises the major segment of the Program.

1.1.1 PROGRAM OBJECTIVES

The objectives of the NASA Geodynamics Program are: (1) to contribute to the understanding of the solid Earth, in particular the processes that result in movement and deformation of the tectonic plates; and (2) to improve measurements of the Earth's rotational dynamics and its gravity and magnetic fields. Studies of new instrumentation and space missions are supported to facilitate the improvement of precise measuring systems by which these phenomena may be assessed.

1.1.2 DESCRIPTION OF PROGRAM RESEARCH AREAS

The Geodynamics Program is subdivided into three main areas: 1) an Earth Dynamics Program; 2) a Crustal Dynamics Program; and 3) a Geopotential Research Program.

The objective of the Earth Dynamics Program is to develop models of polar motion and Earth rotation, and relate studies of global plate motion to dynamics of the Earth's interior. This should lead to an increased understanding of the global structure of the Earth and the evolution of the crust and lithosphere. This research includes studies of the dynamic coupling between different regions of the Earth's interior and its relationship to crustal magnetization, gravity anomalies and tectonic features. A significant portion of this program element includes activities performed under the Crustal Dynamics Project, which makes highly accurate measurements of Earth rotation and polar motion.

Measuring campaigns and modeling studies of crustal deformation in various tectonic settings is the primary objective of the Crustal Dynamics Program. These studies will provide both measurement, analysis, and models which describe accumulation and release of crustal strain, and crustal motions between and within the tectonic plates, particularly the North American, Pacific, Eurasian, and Australian plates. Efforts will include development of quantitative descriptions of the plate tectonic and geological constraints on the motions of measuring sites, including refinements of global plate motion models and block-tectonic models of the western United States. The investigations will compare the long-time geologically determined motion vectors between project sites with the short-time geodetically determined values to test the predictions of geological models.

The Geopotential Research Program applies space and ground measurements to construct gravity and magnetic field models and investigates data analysis techniques and software systems. Studies of the Lageos orbit and the orbits of near-Earth satellites are one of the efforts directed towards advancing gravity field studies. Gravity field data derived from satellite altimetry; satellite-to-satellite tracking and gradiometry; magnetic field data from satellite magnetometers; and ancillary data are used in formulating the models.

1.2 PROGRAM PARTICIPANTS

The NASA Geodynamics Program includes participants from Federal agencies, private and state institutions and universities, in twenty-five countries.

1.2.1 INTERAGENCY COORDINATION

Geodynamics is an interdisciplinary Earth science. A variety of federal agencies are involved in research in one or more aspects of this field. Recognizing that space technology is only one of the possible tools for advancing the understanding of the solid Earth, NASA has sought a close working relationship with the other relevant federal agencies.

In September 1980 an Interagency Agreement involving NASA, NOAA, USGS, DMA, and NSF, established provisions for overseeing the development of space technology for crustal dynamics and earthquake research. The Agreement established a high-level Program Review Board and an Interagency Coordinating Committee, and led to the development of a Federal Implementation Plan for the joint development and use of space systems for the acquisition and analysis of data, for the transition of new technologies from R&D to operational status, and for expansion of the national effort to a global program of geodynamics research. Specifically, three new services are planned: (1) a National Crustal Motion Network by NOAA beginning in 1984; (2) an improved Polar Motion and Earth Rotation Service (Polaris) jointly developed by NASA and NOAA and operational in 1983; and (3) a Local Crustal Motion Network, based on the use of the DOD Global Positioning System (GPS) satellites.

In view of the potential importance of GPS to civilian satellite geodesy, an interagency group including NOAA, DOD, NASA, and USGS has prepared a plan for the development and testing of GPS receiver concepts. This plan provides a basis for coordination of the activities of these federal agencies for testing and eventually selecting the optimum GPS method, based on costs and performance, for federal use.

The interagency Satellite Geodesy Applications Board (previously known as the Geodetic Satellite Policy Board) has existed since 1964 and has agency participation and guidance from NASA, NOAA, and the DMA.

1.2.2 NATIONAL RESEARCH COUNCIL

The National Research Council (NRC) coordinates a variety of activities in geodynamics between the federal agencies, academic scientists, and international groups. In 1970, the NRC recognized the need to foster and encourage studies of the dynamic history of the Earth and established the U.S. Geodynamics Committee (USGC). In addition to acting as a center for U.S. efforts in geodynamics, the USGC represents the United States in the International Geodynamics Program and the Inter-union Commission on Geodynamics. The National Academy of Science of the NRC began an advisory Panel on Crustal Movement Measurements under its Committee on Geodesy and the Committee on Seismology in 1978. The report of this panel in 1981, Geodetic Monitoring of Tectonic Deformation - Toward a Strategy, outlines the scientific rationale for crustal studies and the technology needs. Similarly the Committee on Earth Science of the Space Science Board in its 1982 report, A Strategy for Earth Science from Space in the 1980's. Part I: Solid Earth and Oceans, emphasizes the importance of tectonophysics and its relationship to other Earth sciences.

1.2.3 INTERNATIONAL PARTICIPATION

Many international scientific endeavors are coordinated by the International Council of Scientific Unions (ICSU) and its member Unions. In the 1970's, two ICSU members, the International Union of Geodesy and Geophysics (IUGG) and the International Union of Geological Sciences (IUGS) co-sponsored the International Geodynamics Program. This program was extended by the ICSU in 1980 by establishing the Inter-Union Commission

on the Lithosphere (ICL). Cooperation in the ICL comes from many international organizations, such as the International Association of Geodesy (IAG), the United Nations Educational Scientific and Cultural Organization (UNESCO), the Committee on Space Programs and Research (COSPAR), and the International Astronomical Union (IAU).

International participation in the NASA Geodynamics program is extensive. Of primary interest to the NASA Geodynamics Program are the establishment by other countries of systems for monitoring polar motion and Earth rotation and the measurement of crustal motion and deformation.

Programs of application of space technology to geodesy and geodynamics exist in the Federal Republic of Germany, the Netherlands, France, England, Greece, Austria, Spain, Sweden, Australia, Italy, Japan, Canada and China. In all, tectonic plate motion, polar motion, and Earth rotation are being monitored by laser and/or VLBI stations in 20 countries. Other countries are participating in the NASA program by sponsoring scientists and by providing sites for measurements. In cooperation with these countries NASA plans, in future years, to conduct measurements in the Caribbean, Central and South America, Canada, New Zealand, and the Mediterranean.

Scientists from the Netherlands and the Federal Republic of Germany are constructing two mobile laser ranging stations and have formed a consortium to deploy these stations in the Mediterranean, with the cooperation of scientists from Turkey, Greece, Italy, and Switzerland. Similar stations are being planned by Japan and Italy. The Council of Europe is preparing a comprehensive plan for a program of earthquake research in Europe, which is expected to include the consortium as an important part of research in earthquake prediction. The European Space Agency, NASA, and the Council of Europe are discussing a possible agreement to carry out a cooperative program in which the U.S., German, and Dutch mobile lasers will be used both in Europe, the Western Hemisphere, and elsewhere in the world as the foundation of a global program of space geodynamics. The International Association of Geodesy has established a special subcommission to help coordinate the use of the mobile facilities for global measurement of crustal deformation.

Thus, there is now in existence an international structure to address geodynamic problems in major areas of the world.

SECTION 2. PROGRAM HISTORY

The NASA Geodynamics Program is based on over two decades of research in geodesy, tectonic processes, and earthquake hazard assessment using space techniques. The following is a brief review of these early programs and their accomplishments. A more detailed review of the history of laser ranging (Section 2.3), VLBI (Section 2.4), and geopotential field studies (Section 2.5) follows the sections on the early programs.

2.1 NATIONAL GEODETIC SATELLITE PROGRAM

The period between 1957 and 1965 saw a growth in the number of geodetic satellites and a vast increase in the amount of satellite tracking data that could be used to measure geophysical parameters of the Earth. Through this beginning period of growth, no comprehensive program oversaw the planning and execution of the missions and processing, archiving and evaluating of the results.

The National Geodetic Satellite Program (NGSP) was started in 1965 by NASA primarily in response to the need for improvements in the geodetic and geophysical constants used by NASA in its computation of orbits. The primary focus of the NGSP was to study the Earth's gravity field. There was also a need for a program that would coordinate the efforts of the several groups engaged in satellite geodesy. Furthermore, when the NGSP was started, there was very little systematic work being done on calibration and intercomparison of the different kinds of satellite tracking systems. The need for reliable information on the calibration constants of the tracking systems and on how the systems compared in accuracy and precision with each other was considered great enough to warrant inclusion in the program.

NASA started the NGSP by setting up an extensive ten year program of observation and data reduction. The major participants in the program were NASA's Goddard Space Flight Center and Wallops Flight Center, the Applied Physics Laboratory of Johns Hopkins University, the Smithsonian Astrophysical Observatory, Ohio State University, the Department of Defense, and the National Geodetic Survey (formerly the U.S. Coast and Geodetic Survey). The many activities involved were brought together by designating individuals in the participating organizations as principal investigators.

The requirements of NASA for the NGSP paralleled requirements of other groups both in the United States and abroad. The U.S. Coast and Geodetic Survey was starting its World Geometric Net and needed help in carrying out its field operations and data reduction. The Smithsonian Astrophysical Observatory had the same requirements for its observing network of cameras that NASA had. The U.S. Navy wanted to improve the navigational accuracies of its navigation satellite system, and the Army Map Service wanted satellites suitable for use in constructing its geometric equatorial network.

To provide a suitable and uniformly available set of satellites for the NGSP, the program concentrated its efforts on satellites designed especially for geodetic application: PAGEOS, GEOS 1, GEOS 2, and Beacon Explorers B and C, the latter two equipped with laser retroreflectors. The NGSP achieved its three-part goal of tying together the world's geodetic networks with 10-meter accuracy in a single center-of-mass system, representing the gravity field to degree and order 15 with an accuracy of 5 parts in 10^8 , and intercomparing major tracking systems at the 10-meter level.

Five satellites were launched under the NGSP:

- 1) Explorer 22 (Beacon Explorer B); launched October 10, 1964; orbit 1075 x 1035 km @ 79.7° inclination. In addition to ionospheric studies, this satellite provided the first instance of ground-based satellite laser tracking.
- 2) Explorer 27 (Beacon Explorer C); launched April 29, 1965; orbit 1300 x 900 km @ 41.1° inclination. This mission carried ultrastable oscillators for precise Doppler tracking of orbital perturbations for gravity field determination. Laser tracking experiments and ionosphere studies were continued.
- 3) Geodetic Earth Orbiting Satellite (GEOS 1 - Explorer 29); launched November 6, 1965; orbit 2300 x 1100 km @ 59.3° inclination. This mission carried instrumentation provided by several participating agencies: a U.S. Navy Doppler system, a U.S. Army electronic ranging system (SECOR), U.S. Air Force optical beacons, NASA laser cube corner retroreflectors, and a GSFC range and range-rate system. This combination of instruments accomplished two important objectives: (a) most of the observation capability of the U.S. could be focused on one satellite; and (b) errors in a particular system could be discovered and corrected by reference to others.
- 4) PAGEOS 1 (Passive GEOS); launched July 1, 1966; orbit 4900 x 3500 km @ 86.4° inclination. This mission consisted of the use of an ECHO 1 type, aluminized Mylar balloon, for optical sighting in a sun-reflection mode. By observing PAGEOS 1 against the star background, stations determined their orientation to one another.
- 5) GEOS 2 (Explorer 36); launched January 11, 1968; orbit 1600 x 1100 km @ 105.8° inclination. This mission was nearly identical to GEOS 1 with the addition of a C-band transponder and reflector, and a Continuous Wave laser detector. The retrograde orbit provided a different satellite inclination to better separate the coefficients of the mathematical representation of the gravity field. The C-band transponder was used to support the calibration and evaluation of the NASA and DOD C-band radar systems.

2.2 EARTH AND OCEAN DYNAMICS APPLICATIONS PROGRAM

Although the NGSP was begun as an effort to study the Earth's gravity field and to improve knowledge of the geodetic constants, it soon became evident that a sufficient improvement in the accuracies obtainable could lead to the ability to make direct measurements of crustal deformation and plate motion. A conference was held at Williamstown, Massachusetts, in 1969, at which NASA representatives met with leaders of the science community to outline the requirements and objectives of a program in geodesy, geodynamics, and oceanography. This led to the development of an Earth and Ocean Dynamics Applications Program (EODAP) plan in 1972. The Geodynamics Experimental Ocean Satellite (GEOS 3), initiated in 1970 and launched in 1975, represents an interim step between the essentially completed NGSP and the emerging EODAP. EODAP subsequently split into two programs, the Geodynamics Program and the Oceanic Processes Program.

The EODAP plan called for the development of centimeter-level VLBI and laser ranging systems, as well as a number of flight missions (Figure 1) besides GEOS 3, including Lageos, Seasat 1 and 2, Magsat, and Geopause-Gravsat.

Under EODAP, the Earth Dynamics Monitoring and Forecasting Program was established to direct the development of VLBI and laser ranging systems and to conduct research in solid Earth modeling and analysis. (A similar program was established to direct ocean studies.) This Earth Dynamics Monitoring and Forecasting Program was the direct predecessor to the current Geodynamics Program. The principal solid Earth program established under EODAP and carried over to the current NASA program was the Tectonic Plate Motion (TPM) Program. The TPM program included a number of smaller experimental projects:

- 1) The San Andreas Fault Experiment (SAFE), a laser ranging experiment initiated in 1972 to measure plate movement along the San Andreas Fault in California (Figure 2). The SAFE measurement campaigns were repeated approximately every two years and are continuing under the Crustal Dynamics Project
- 2) The Pacific Plate Motion Experiment (PPME). PPME established requirements and instrumentation for measuring relative plate motion between the North American and Pacific plates; and
- 3) The Astronomical Radio Interferometric Earth Surveying (ARIES) Project. Under ARIES, the first mobile VLBI station, MV-1, was developed and deployed. The ARIES MV-1 established early instrumentation requirements for mobile VLBI systems and was used to demonstrate the applicability of VLBI in measuring baseline lengths in Southern California. The ARIES project also developed the plans for an improved mobile VLBI, the MV-2.

2.3 LASER RANGING DEVELOPMENT

The development of satellite laser ranging (SLR) systems (Figure 3) started in the early 1960's, soon after the invention of the laser. SLR

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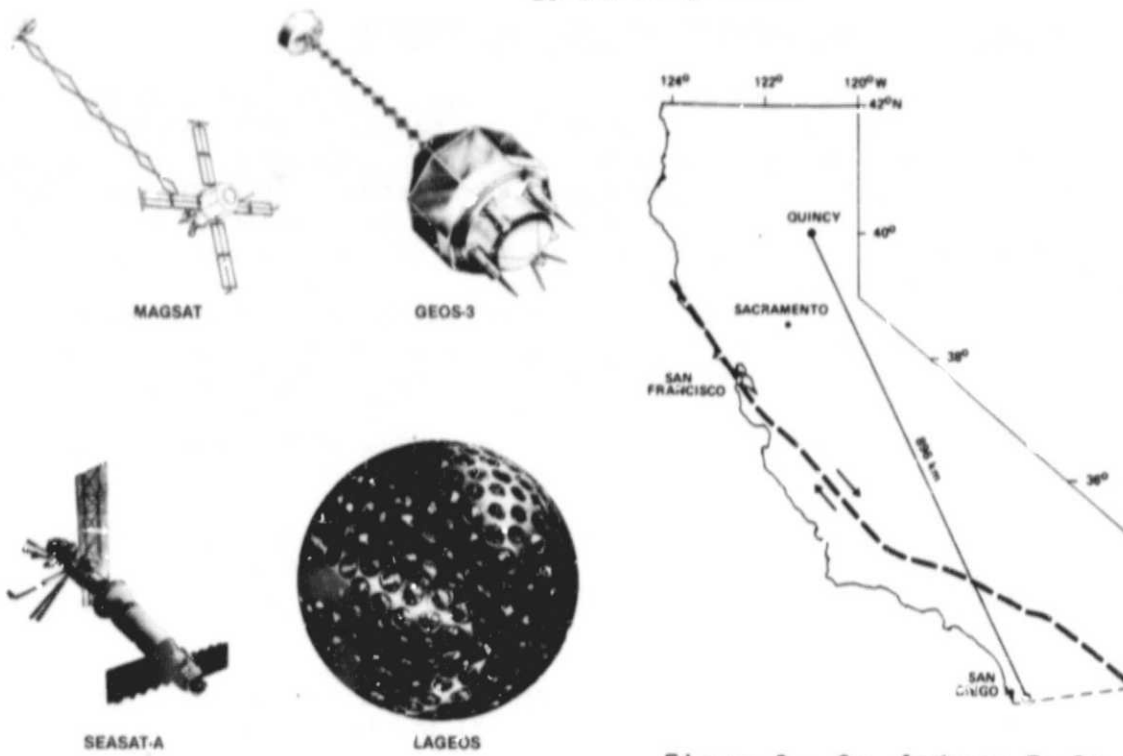


Figure 1 - EODAP flight missions

Figure 2 - San Andreas Fault
Experiment

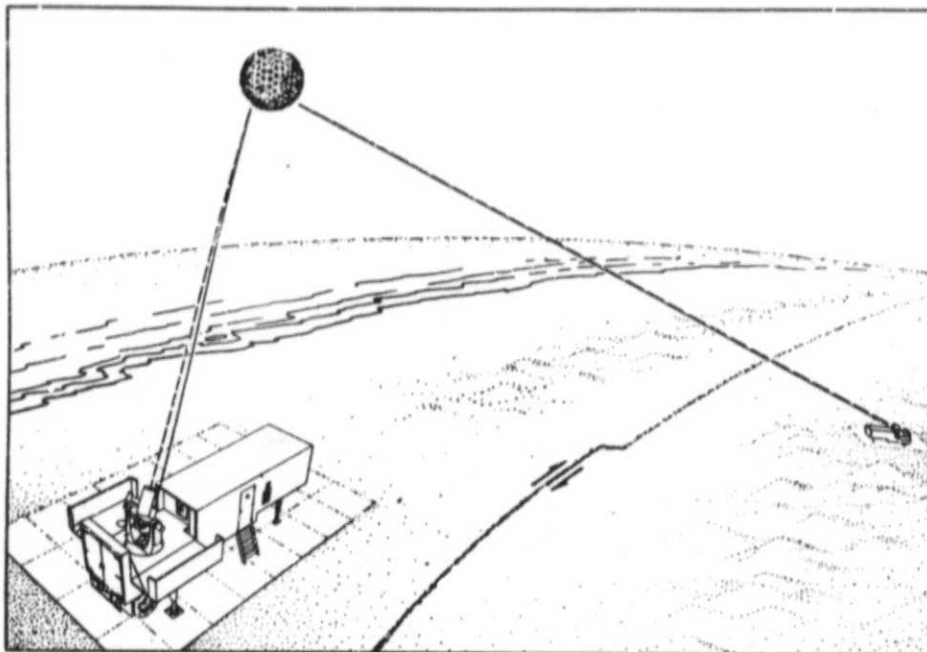


Figure 3 - Satellite Laser Ranging

was originally developed as an experimental tracking system for orbit determination and satellite geodesy. Very shortly thereafter, researchers realized the potential of SLR for making precise terrestrial measurements, and the era of using space-derived techniques for accurate measurement of geophysical parameters was opened. SLR has been used to determine station position, baseline lengths, and variations in polar motion and Earth rotation; and the data have aided in determination of the gravity field and solid Earth tides.

In the past fifteen years, thirteen satellites equipped with cube corner retroreflectors have been launched by the U.S. and other countries. The accuracy of the measurements has improved greatly; the earliest ranging systems achieved a precision of a few meters, and the present precision is 3-5 cm.

The earliest satellites used for laser ranging (the Explorer /GEOS series) were in low-altitude orbits (1000 km) which are significantly affected by atmospheric drag, solar radiation pressure, and anomalies in the gravity field. These effects complicated the orbital calculations, and consequently the laser ranging analysis, making it difficult to produce accurate measurements of positions on the Earth's surface. NASA therefore launched a Laser Geodynamics Satellite (Lageos) in 1976 (see Figure 1). This very dense spherical satellite has a high-altitude (5900 km) stable orbit and made possible great improvements in crustal measurements using SLR. Additionally, more sophisticated gravity field models, determined in part by the results of SLR measurements to low-altitude satellites, helped reduce the early position recovery limitations caused by imprecise knowledge of orbit position and the effects of the gravitational field on measurements. So by the latter part of the 1970's, the primary limitation on the precision of SLR became the errors inherent in the laser systems. Current efforts are concentrating on improving SLR accuracies to the 1-2 cm level by improving the design of laser systems and by incorporating further improvements in Earth models.

Lunar laser ranging (LLR), in which laser systems range to retroreflectors on the Moon has experienced a parallel development. In the late 1960's, NASA included the Lunar Ranging Retroreflector Experiment in the Apollo program, and retroreflectors were placed on the Moon by the crews of Apollo 11, 14, and 15 (see Figure 4). The Soviets placed two French-made retroreflectors on the Moon in their Luna program. More information on the technique of LLR is included in Section 4.2.1.2.

The concept of LLR was proposed in the late 1950's, when the gravitational research group at Princeton University showed that precision tracking of a high-altitude satellite could be used to measure possible changes in the gravitational constant. Additionally, LLR has provided information on relativity studies and has helped in determining the orbit of the Moon, lunar librations, constraints on the interior structure of the Moon, and the evolution of the lunar orbit. Since the first LLR measurements in 1969 from the McDonald Observatory of the University of Texas at Austin, LLR has been routinely performed with a mean range accuracy of about 9 cm.

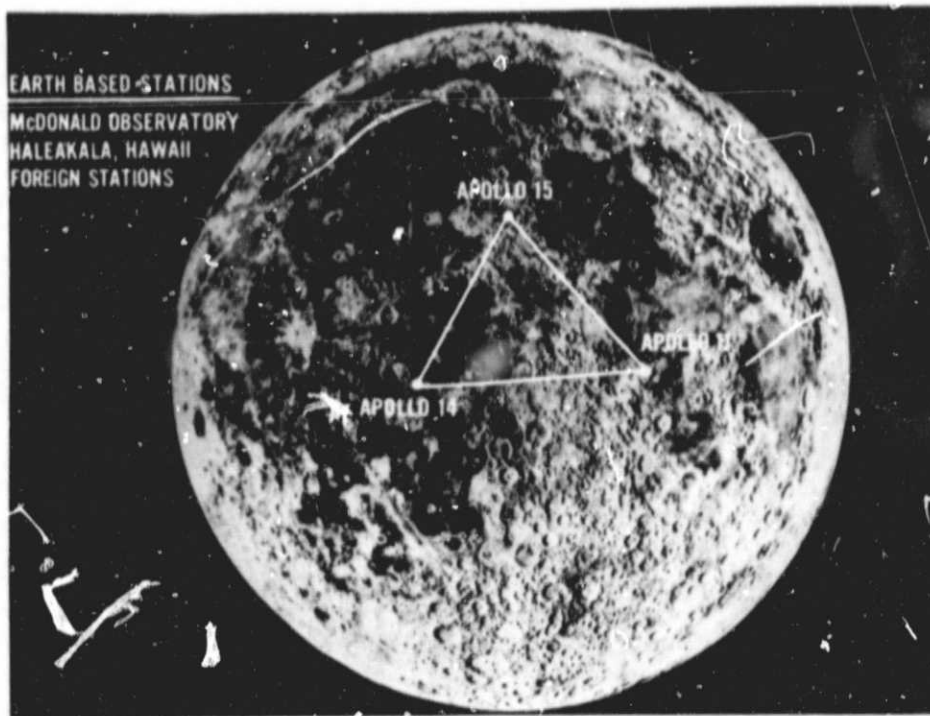


Figure 4 - Laser ranging retroreflector sites

As more geophysical applications for laser ranging became apparent, so did the need for the development of a mobile laser system which could be moved where needed and could provide more areas with laser ranging coverage. The first mobile laser station was built at Goddard Space Flight Center in 1967. In this first-generation system, called Moblas-1, the laser transmitter and receiver were affixed to a movable Nike-Ajax mount, and the electronics system was housed in a separate trailer. The first fully mobile laser station was built in 1971. This second-generation system, called Moblas-2 (Figure 5), had all its instrumentation in a single van. Moblas-3 was built in 1975 and was basically an improved Moblas-2 system.

All three early Moblas stations demonstrated high reliability and decimeter accuracy, and were the only operating mobile laser ranging systems through the mid-to-late 1970's. By 1979, seven Moblas stations were deployed in the U.S., Australia, and the Pacific, forming a global network of both stationary and mobile laser ranging facilities used to track Seasat and to maintain the accuracy of the Lageos orbital ephemeris. Additionally, the laser ranging network was used to make observations on polar motion and Earth rotation and to begin studies of tectonic plate motion and plate stability.

In the spring of 1978, the University of Texas began the construction of a highly mobile station called the Transportable Laser Ranging Station (TLRS-1). This station is mounted in one self-contained truck (Figure 6), and only a few hours are required to set or disassemble the station at any site. The TLRS-1 first ranged to Lageos on November 1, 1979.

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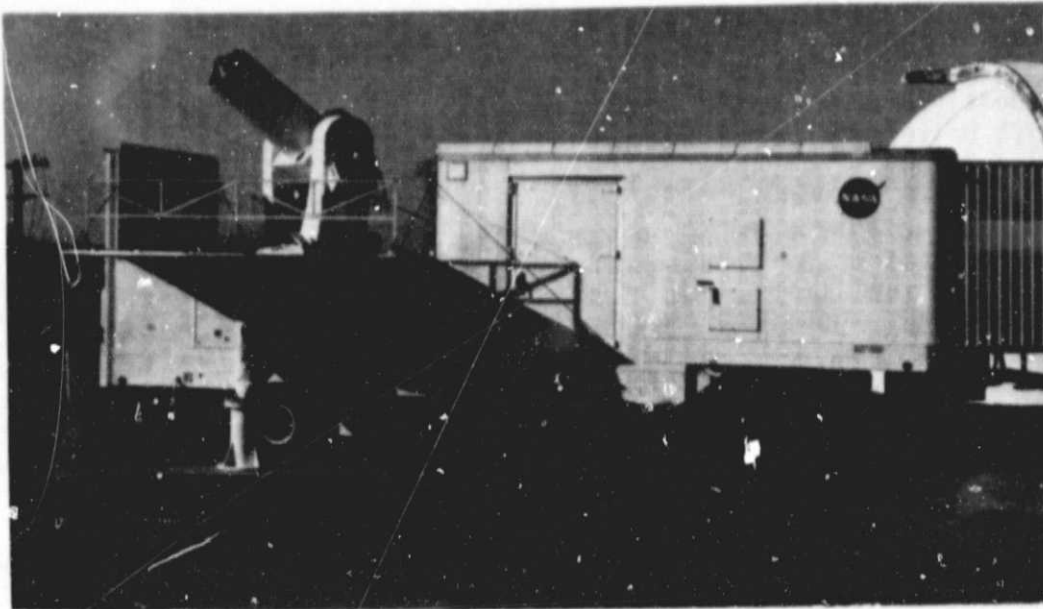


Figure 5 - MOBLAS-2, -3 laser station

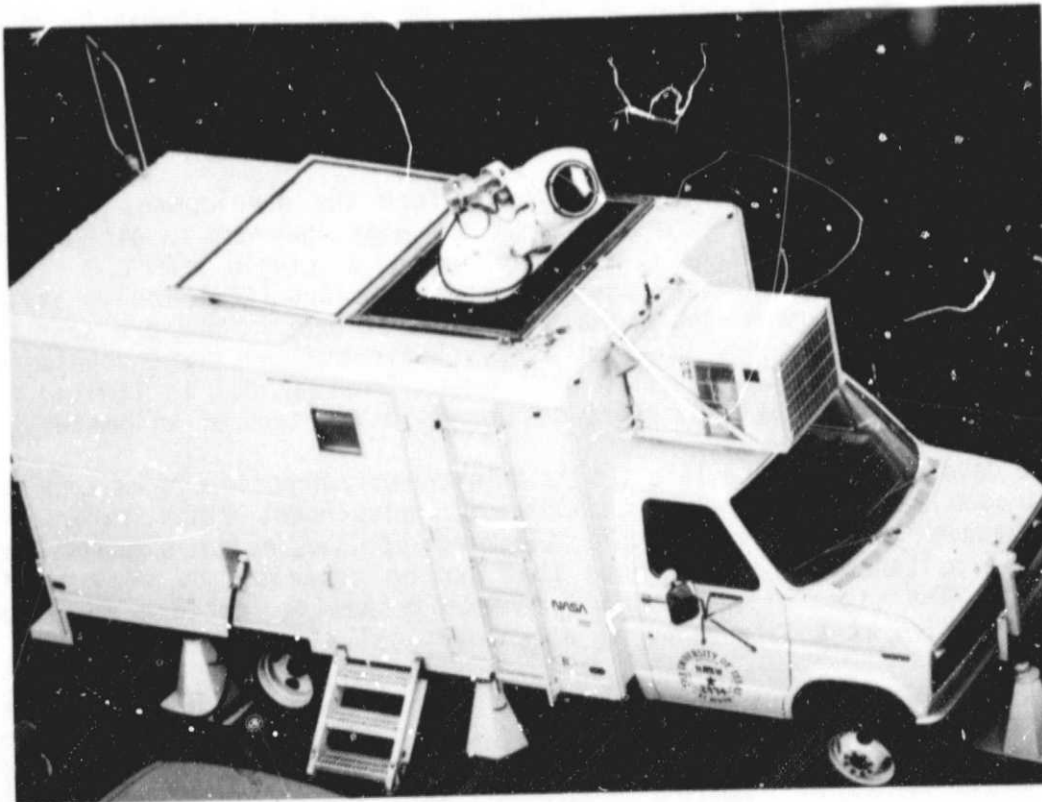


Figure 6 - TLR-1

A second highly mobile laser system (TLRS-2) has been constructed at the NASA Goddard Space Flight Center (GSFC) and will be deployed in 1982. TLRS-2 is modular, and can be disassembled for shipment. In Europe, an independently designed highly mobile laser station is under development by the Delft University of Technology. Additional information on TLRS is in Section 4.2.1.4.

The Smithsonian Astrophysical Observatory (SAO) under contract to NASA, has participated in the development and use of SLR systems since 1965. A prototype of the current SAO lasers was established in Mt. Hopkins, Arizona, in 1967. In addition to performing laser operations through 1979, this station was used to test engineering modifications and to develop laser technology. Four SAO lasers performed routine daily ranging operations and were upgraded in 1982 to provide higher accuracy ranging measurements. Currently only the SAO laser station in Arequipa, Peru, is operational.

An international system of laser ranging stations provides geodetic measurements for most of the Earth. Figure 7 shows the global network of U.S. and foreign laser ranging stations in existence in 1979.

2.4 VLBI DEVELOPMENT

Geodetic VLBI is an outgrowth of microwave radio interferometry developed by radio astronomers to measure the positions of astronomical radio sources and to define the source structure. The delay in microwave signals received simultaneously at two antennas separated by a known distance can be used to calculate the source location and to survey its structure. Likewise a known source can be used to determine the distance between two antennas (Figure 8).

In early microwave radio interferometry, before the development of very accurate clocks, the clock errors of drift and bias inherent in attempting to correlate recorded signals required using a single clock. This technique is known as Connected Element Interferometry (CEI) and is still in use. In CEI (Figure 8) the signals received at one antenna are sent to the other via a cable communications link. The cross-correlation between antenna signals is accomplished in real time. However CEI is limited by the cable length to relatively short distances (i.e., tens of kilometers).

With the development in the late 1960's of extremely precise clocks such as the hydrogen maser, very-long-baseline or independent clock interferometry became possible. In VLBI, incoming stellar radio signals are received simultaneously by antennas that can be separated by very great distances. The signals are recorded at both receiving stations and then cross correlated at a later time at a central analysis facility.

Overall, the development of geodetic VLBI has roughly paralleled the development of laser ranging. By the late 1960's its advantages in making geophysical and geodetic measurements were recognized, and in the early 1970's measurements of baseline length and Earth orientation using VLBI were initiated.

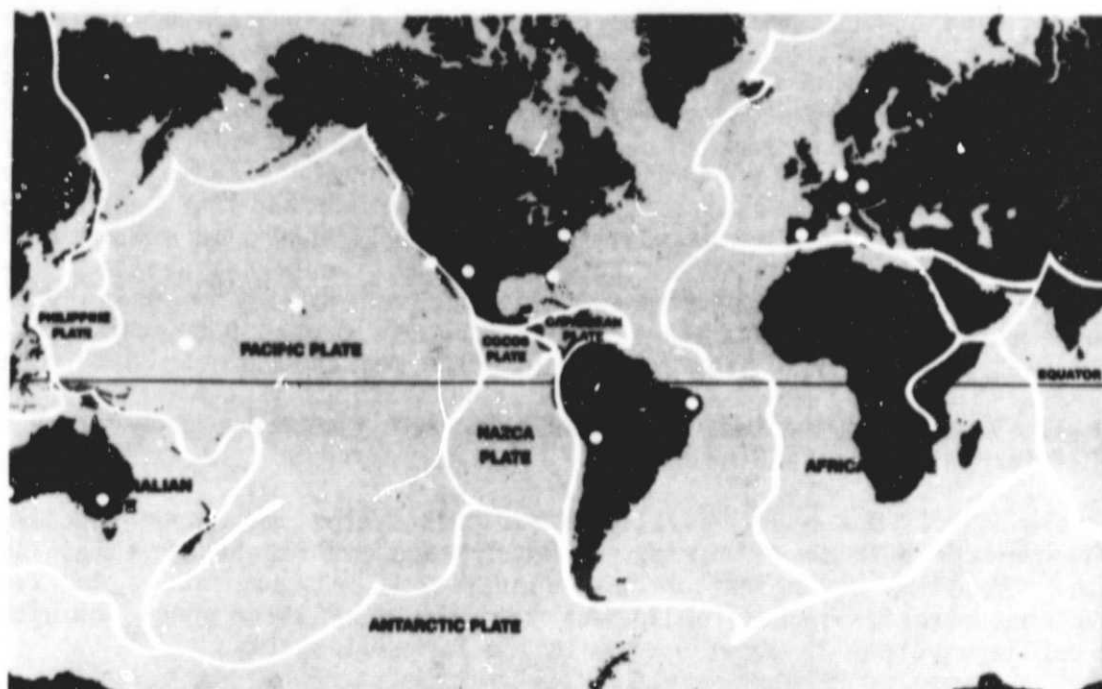


Figure 7 - Global laser ranging stations

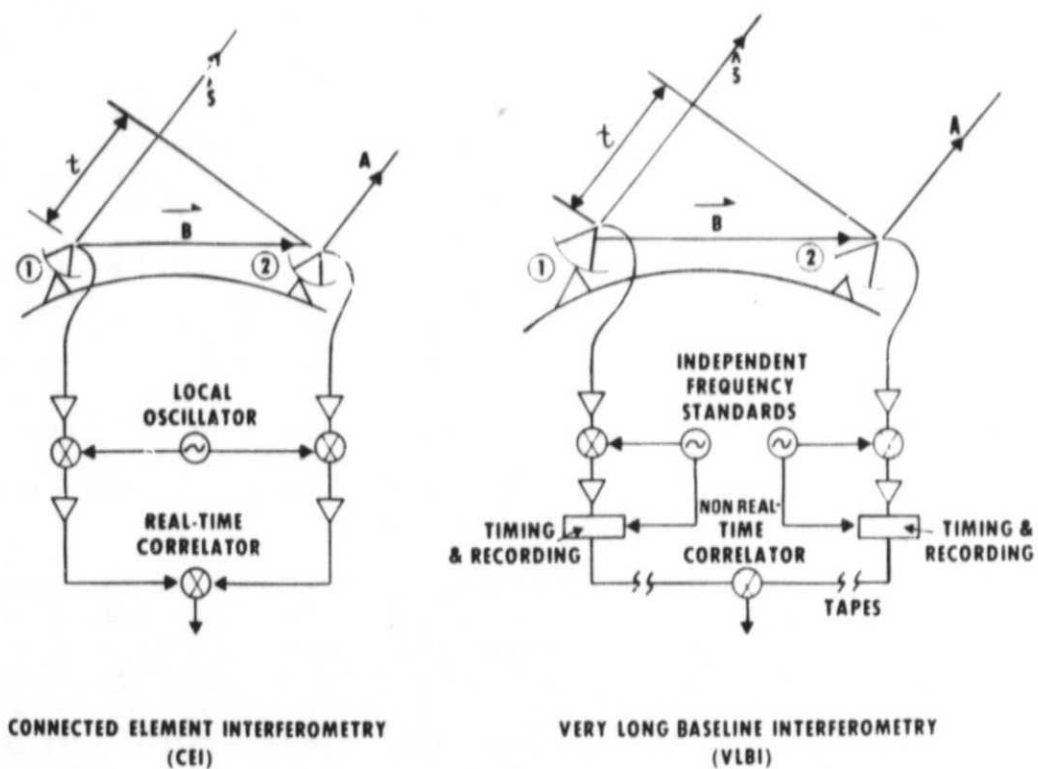


Figure 8 - Astronomic radio interferometry techniques

The precision of VLBI measurements has gone through several improvements as the data acquisition systems and the analysis techniques have been improved. The initial data acquisition system, known as the Mark-I, was developed primarily to study the structure of radio sources. A network of radio observatories - Onsala Space Observatory in Sweden, the National Radio Astronomy Observatory (NRAO) in West Virginia, the radio astronomy telescope at Haystack Observatory in Massachusetts, and the Deep Space Network facility at Goldstone, California - were involved in making VLBI measurements and determining the capabilities of the Mark-I system. The Mark-II system was developed to evaluate the feasibility of using VLBI measurements in tracking and navigation of deep space missions. Particular emphasis was placed on using VLBI measurements to determine universal time (UT1) and polar motion. The stations that pioneered the Mark-II system were the Deep Space Network, with operating observatories in California, Spain, and Australia.

In the middle 1970's the Mark-III data analysis system, developed specifically for the purpose of making geodetic measurements, began a testing phase. Baseline determination between Haystack, Massachusetts, and two radio observatories in California improved from about 16 cm precision with the earlier systems to about 4 cm with the Mark-III system.

The knowledge gained through the earlier Mark-I and -II VLBI studies of the early 1970's aided in improving the accuracies of the Mark-III VLBI. Two of these developments, the improved ability to model the effects of atmospheric water vapor content on the speed of signal propagation through the troposphere, and the effects of ionospheric refraction on VLBI measurements, led directly to instrument developments in the Mark-III VLBI systems. The effects on ionospheric refraction were first observed and measured in 1979 with a Mark-III VLBI system by recording signals from two microwave frequencies simultaneously (X and S-band). To account for the effects of water vapor content in the troposphere, water vapor band microwave radiometers were developed and were installed at the Haystack Observatory and the Owens Valley Radio Observatory in California. Efforts to eliminate these modeling errors continues, and it is hoped that the current 2-3 cm residual tropospheric refraction correction will be reduced to 1 cm with continued water vapor radiometer measurements taken in conjunction with VLBI measurements. Other improvements have also contributed to the current improved ability to make VLBI measurements. These include upgrading the frequency recording standards by using very stable hydrogen maser clocks and correcting for errors in the models of solid Earth tides and the Earth's nutation by incorporating the early VLBI and laser ranging study results into the current models. Figure 9 shows the locations of the fixed VLBI stations in 1979.

The development of mobile VLBI stations roughly paralleled the development of mobile laser ranging stations (Figure 10). The first mobile VLBI system, MV-1, also known as ARIES, began measurements in 1973 using a 9-meter erectable antenna and a surplus Nike antenna. Baseline lengths determined by MV-1 in Southern California agreed within six cm with National Geodetic Survey (NGS) ground-based electro-optical distance measurements (which have an instrument accuracy of 6 cm).

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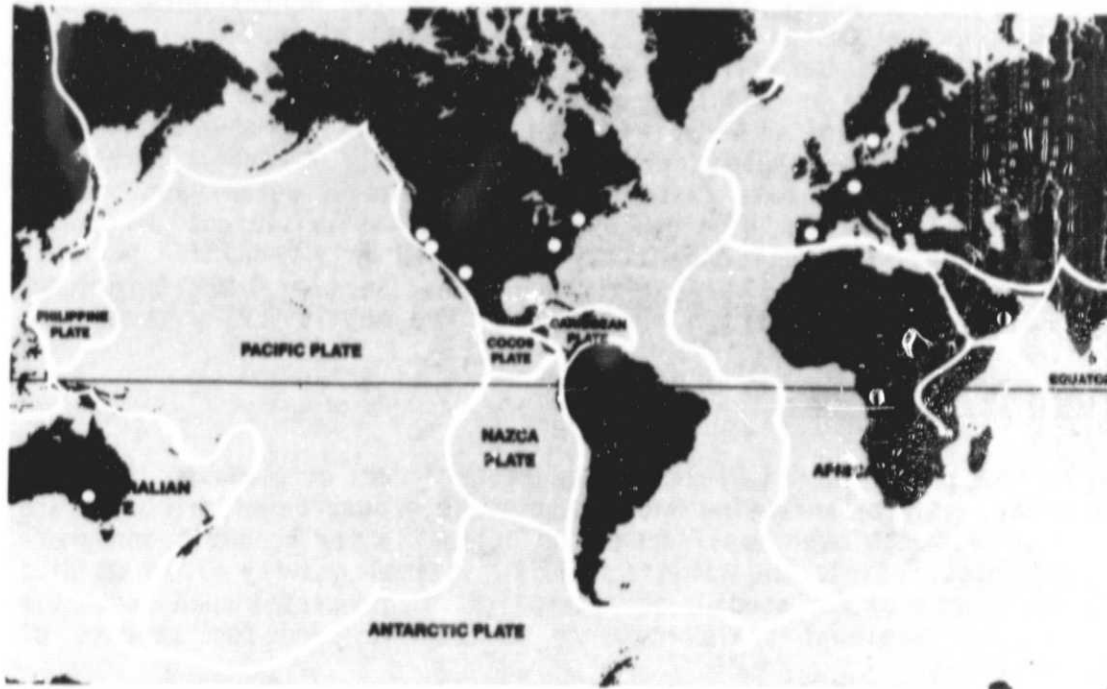


Figure 9 - Global VLBI stations

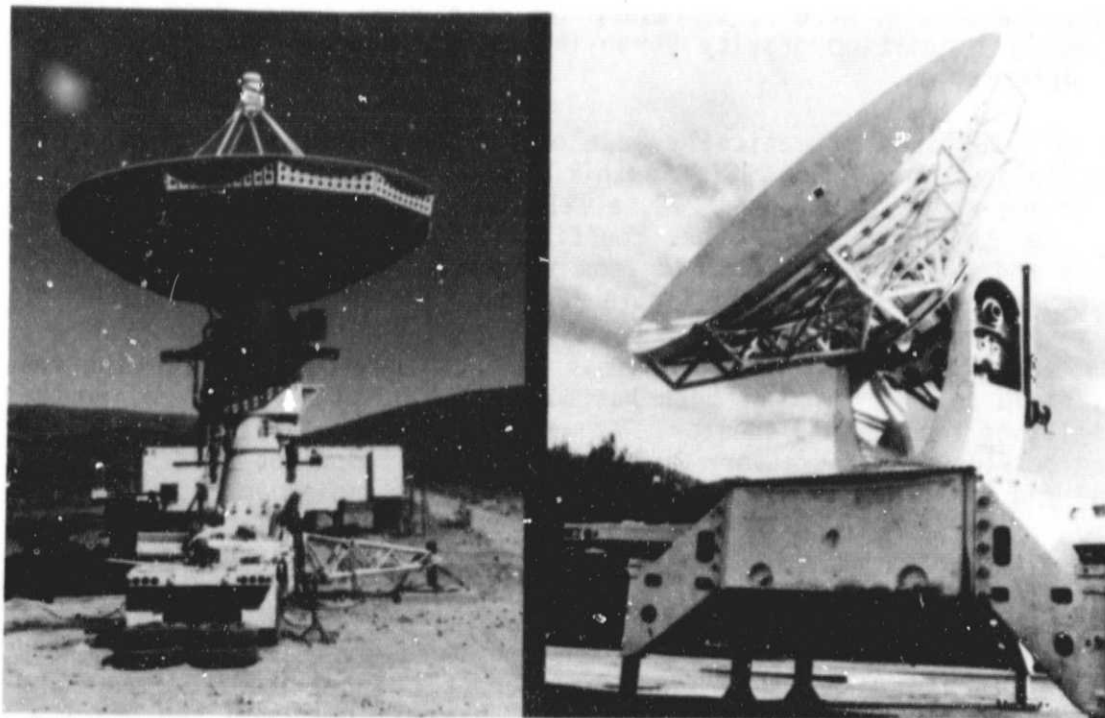


Figure 10 - Mobile VLBI

The MV-1 requires anywhere from several weeks to two months between site visits. To improve system mobility, work was started in 1978 on a more highly mobile VLBI station with a 4-meter antenna, MV-2. The site transition time for this station is about a week. To improve system performance, modifications of MV-1 and -2 were initiated in 1981 and included addition of S-band reception (these systems previously used only X-band); conversion from Mark-II to Mark-III data systems; and additions of water vapor radiometers. Also in 1981 design of a new system (MV-3) was initiated. MV-3 will have a 5 m antenna, Mark-III capability and should only require 4 hours to either set up or disassemble the entire operation. Section 4.2.2.2 includes a further discussion of the instrumentation of the mobile VLBI systems.

2.5 GRAVITY FIELD STUDIES

Studies of the gravitational field are an integral part of geodesy. Prior to the space age, gravity surveying was conducted by ground-based, airborne and shipborne instruments over small areas and primarily for geodetic and prospecting purposes. Since the first satellite, global gravity field studies have become essential for studies of internal Earth processes such as mantle convection, for regional scale resource assessment, and for studies of oceanic processes.

Because of the Earth's roughly spherical shape, the gravity field is commonly described as a series expansion in spherical harmonics. Prior to 1957, the only terms estimated were the second, third, and fourth degree zonal series. The second and fourth degree terms are related to the flattening or oblateness of the Earth. The Earth's oblateness was first postulated by Newton in his Principia Mathematica. Between 1867 and 1957, the only advances in gravity field studies were 1) to refine the oblateness factor from 1/230 to 1/297 and 2) to develop gravity surveying as a method of extracting sub-surface information.

The early satellites dramatically accelerated developments in geodesy and gravity field studies. In 1957, Sputnik 2 was used to calculate the flattening as one part in just over 298, a value altered very little since then. In 1959, for the first time, other coefficients were accurately calculated; the third and fifth zonal harmonic from Vanguard's orbit to give the pear-shaped component of the Earth's figure (Figure 11).

In 1964, non-zonal harmonic expressions were calculated, representing the gravity field as a function of both latitude and longitude and revealing the ellipticity of the Earth's equator. At present the gravity field expression has been developed, in just over 20 years, from a 2-component zonal harmonic to zonal and non-zonal harmonics complete to degree and order 36.

The initial advances made in satellite geodesy led to the Army, Navy, NASA, Air Force (ANNA) mission, the first satellite to be launched primarily for geodetic purposes. The ANNA mission was carried out under the auspices of the Department of Defense in 1962; mission management was subsequently turned over to the NASA-managed National Geodetic Satellite Program. The NGSP led to the calculation of approximately 250 coefficients of the gravitation field expansion, corresponding to a harmonic expansion through degree and order 15.

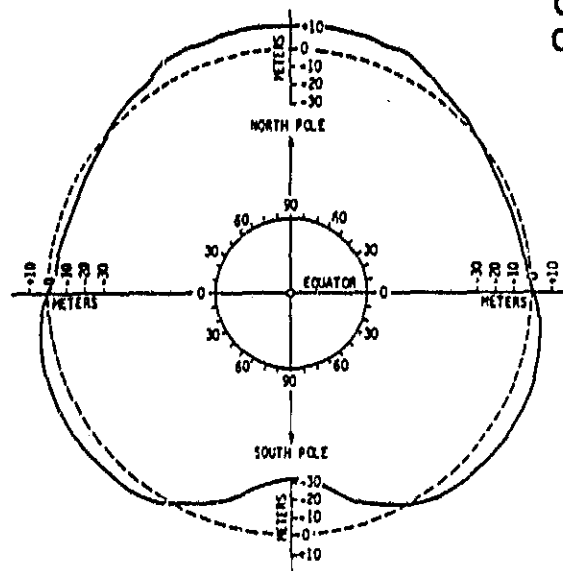


Figure 11 - Pear-shaped component of the Earth's figure

The NGSP produced two major analytical models of the Earth's gravitational field, the Standard Earth III (SE III) by the Smithsonian Astrophysical Observatory, and the Goddard Earth Model 6 (GEM-6) by GSFC (Figure 12).

The accuracy of gravitational field models depends on the satellite observation data as gathered by the tracking networks. The NGSP provided a very large amount of useful information on the errors associated with the tracking systems, but the information unfortunately could not be fully utilized during the lifetime of the NGSP.

Improvements of the quality and resolution of gravity field models over those generated during the NGSP have resulted from three major developments: first, the improvement in the satellite observation data, a direct result of the NGSP; second, the advent of satellite-to-satellite tracking; and third, the beginning of satellite altimetry from Skylab, GEOS 3, and Seasat 1.

Until the early 1970's, a large portion of the satellite observation data were optical right ascension and declination, gathered mostly from the Baker-Nunn camera network. A second observation technique was the radio Doppler tracking of satellites. This technique reached a high degree of perfection in the 1960's.

To these methods has been added laser tracking, developed during the NGSP. The optical and Doppler tracking offered accuracies of 5 to 10 m in position, but laser tracking allows the distance to the satellite to be measured with an accuracy of less than 10 cm. When the accuracy of laser tracking became established, more laser ranging systems were deployed and more satellites were equipped with cube corner retroreflectors. In addition, satellites were designed specifically for laser ranging (i.e., Lageos and the French satellite - Starlette).

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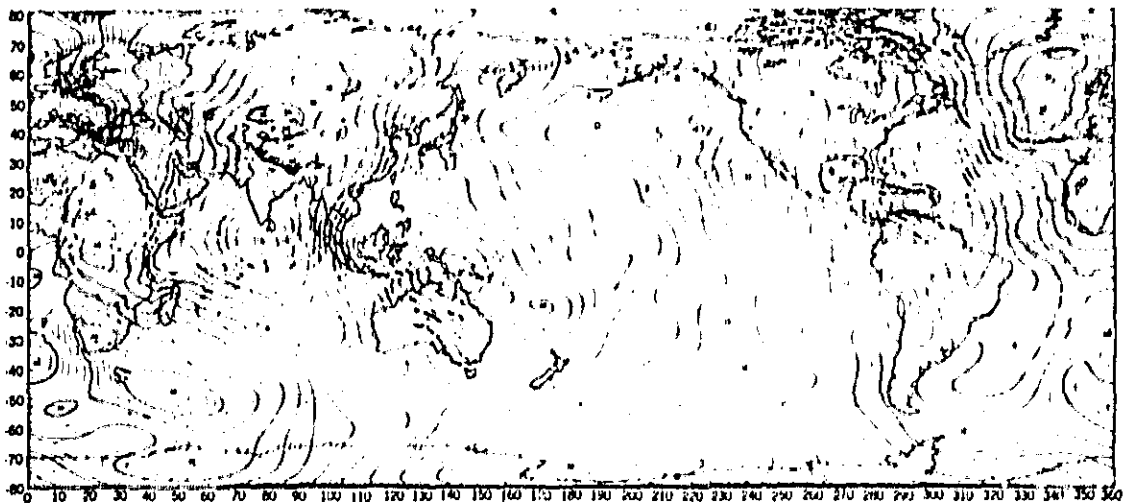


Figure 12 - GEM-6 gravimetric geoid (contour interval, 2 meters)

The most recent advance in satellite tracking for geodetic purposes is satellite-to-satellite tracking (Figure 13), first used with the GEOS 3, Apollo-Soyuz Test Program (ASTP) and ATS 6 missions. In this method a low Earth orbiting satellite (GEOS 3, Apollo) is tracked by a geosynchronous satellite (ATS 6) and variations in the relative acceleration of the two spacecraft are used to identify anomalous gravity features. The major advantage of this technique is the extensive coverage, continuous for nearly half an orbit, as opposed to a series of tracking passes each of only a few minutes duration. For Apollo (240 km altitude), $5^\circ \times 5^\circ$ anomalies have been resolved to about ± 7 mgal in the South Atlantic and Indian Ocean areas.

The most recent instrumental development in gravitational field modeling has been satellite altimetry, discussed in Section 4.2.4.2. Atmospheric and tidal forces causing waves and currents cause the sea level to change, but these effects are roughly two orders of magnitude less than gravity effects. Altimetric observations of sea level can thus be used to determine the marine geoid and thus, by inversion, the gravity field.

The first Earth orbiting altimeter was carried on Skylab in 1973. The results were not extensive but demonstrated its feasibility for making detailed measurements. GEOS 3 (see Figure 1) provided the first extensive set of altimetry data. Included in such models as GEM-10C, the altimetry data augmented by surface gravimetry have expanded the gravitational model from degree and order 36 (GEM-10B) to degree and order 180. In 1978 Seasat carried a third altimeter into orbit; it had an accuracy of ± 10 cm.

Despite the advances made in satellite altimetry, the gravitational field model for solid Earth and oceanographic studies and orbit determination can still be improved. More accurate models are needed for studies of tectonic processes and both Earth crustal structure and Earth interior composition and structure. The current geoid model appears to be accurate to only ± 45 cm, but for oceanographers wishing to determine geostrophic

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velocities from altimetry data, the model should be accurate to a few centimeters. More advanced analysis of existing data and of the data acquired by the planned Geopotential Research Mission (GRM) should provide this accuracy.

Plans for the GRM have evolved from recommendations of the Panel on Sea Level and Gravity at the Committee on Geodesy of the NRC and a Gravsat User Working Group initiated by NASA. The GRM mission will advance the knowledge of the geopotential to an accuracy of about 1-3 mgal at a spatial resolution of 100km and the geoid to an accuracy of better than ± 10 cm. Additional information on the GRM concept can be found in Section 5.3.2, Geopotential Research Program Plans.

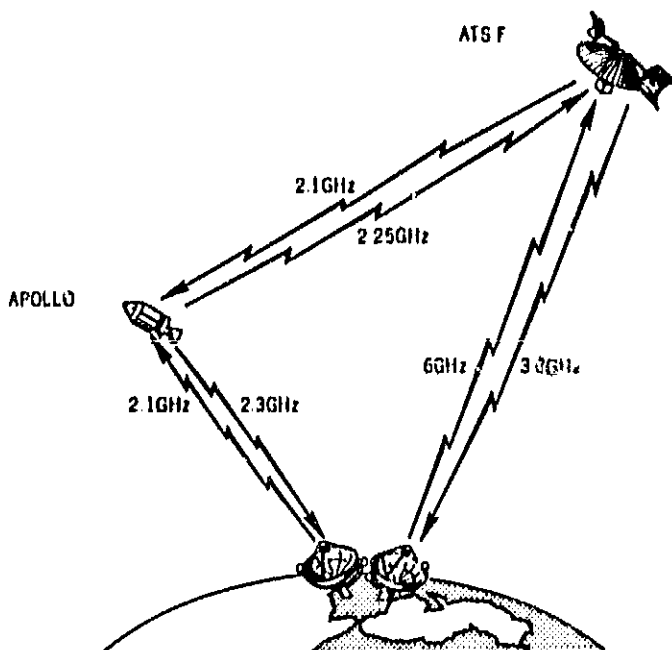


Figure 13 - ATS 6/ASTP satellite-to-satellite experiment

2.6 MAGNETIC FIELD STUDIES

Satellite measurements of the geomagnetic field began with the launch of Sputnik 3 in May 1958 and have continued sporadically in the intervening years. Table 1 is a list of spacecraft that have made significant contributions to our understanding of the near-Earth geomagnetic field prior to the launch in 1979 of the Magnetic Field Satellite (Magsat). Of the earlier satellites, each had its own limitations, ranging from a lack of global coverage caused by the absence of on-board tape recorders to limited accuracy due either to instrumental shortcomings or to ambient spacecraft fields. Prior to Magsat, only the Polar Orbiting Geophysical Observatory (POGO) satellites (OGO 2, 4, and 6) had provided an accurate, global geomagnetic survey. Their alkali vapor magnetometers provided measurements of the field magnitude over an altitude range of about 400 to 1500 km.

Table 1
SATELLITES THAT HAVE MEASURED THE NEAR-EARTH GEOMAGNETIC FIELD

Taken from R. Langel, "Magsat Scientific Investigations" in
Johns Hopkins APL Technical Digest, Vol. 1, No. 3, p. 215

Satellite	Inclination (degs)	Altitude Range (km)	Dates	Instrument	Approximate Accuracy (nT)	Coverage
Sputnik 3	65	440-600	05/58 - 06/58	Fluxgates	100	USSR
Vanguard 3	33	510-3750	09/59 - 12/59	Proton	10	Near ground station*
1963-38C	Polar	1100	09/63 - 01/74	Fluxgate (1-axis)	30 - 35	Near ground station
Cosmos 26	49	270-403	03/64	Proton	Unknown	Whole orbit
Cosmos 49	50	261-488	10/64 - 11/64	Proton	22	Whole orbit
1964-83C	90	1040-1089	12/64 - 06/65	Rubidium	22	Near ground station
OGO 2	87	112-1510	10/65 - 09/67	Rubidium	6	Whole orbit
OGO 4	86	2-938	07/67 - 01/69	Rubidium	6	Whole orbit
OGO 6	82	111-1098	06/69 - 07/71	Rubidium	6	Whole orbit
Cosmos 321	72	270-403	01/70 - 03/70	Cesium	Unknown	Whole orbit
Azur	103	384-3145	11/69 - 06/70	Fluxgate (2-axis)	Unknown	Near ground station
Triad	Polar	750-832	09/72 - present	Fluxgate	Unknown	Near ground station

*"Near ground station" indicates no on-board recorder. Data were acquired only when the spacecraft was in sight of a station equipped to receive telemetry.

The POGO data have been used by several investigators, who have constructed and published a model of the main field, a global magnetic anomaly map (Figure 14), and the analytical description and interpretation of magnetic ionosphere disturbances. One of the principal contributions of the POGO satellites has been to make available a truly global distribution of data within a short enough time interval to represent the secular variation accurately.

Although POGO data were global and taken over a short time span, the limitation of measuring only the field magnitude resulted in some ambiguity in the field direction in spherical harmonic analyses based on POGO data alone. This ambiguity has been removed by the acquisition of global vector data with Magsat.

The launch of the Magsat in October 1979 opened a new era in global geomagnetic surveying. For the first time, a global survey of the vector components of the geomagnetic field was obtained. Magsat carried a three-axis vector magnetometer and a scalar magnetometer. The primary goals of the mission were to obtain global measurements of the main geopotential field and of geomagnetic crustal anomalies. These measurements have been used in the updating of magnetic charts and maps and in the refining of the geophysical models which describe the components and the nature of the geomagnetic field. The modeling of the main field also permits analysis of crustal anomalies which in turn are used as indicators of the underlying material density, type and structure (Figure 15).

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Magsat re-entered the Earth's atmosphere on June 11, 1980. Initial field models were provided in 1980 to Magsat investigators, and the initial results were presented in early 1981. Initial processing of all Magsat data was completed in 1982. For further information on Magsat, see Section 4.2.5.2.

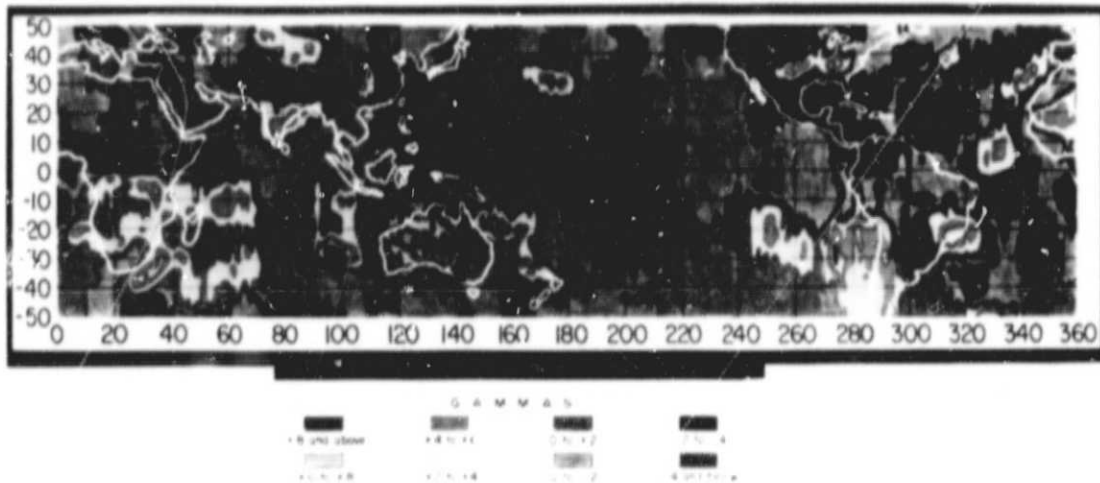


Figure 14 - Global magnetic anomalies from Orbiting Geophysical Observatory data

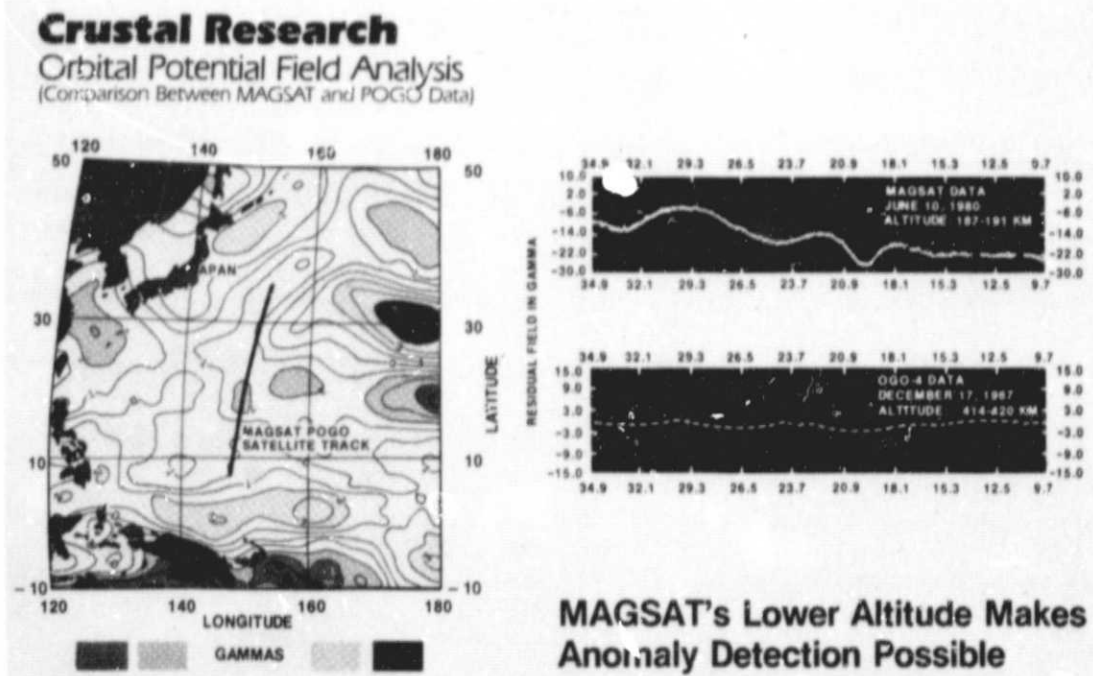


Figure 15 - Orbital potential field analysis

SECTION 3. SCIENTIFIC BASIS

This section provides an overview of the scientific concepts upon which the NASA Geodynamics Program is based. It is divided into three primary areas: Earth dynamics, crustal dynamics and geopotential fields. This is not to imply that these are isolated phenomena. Quite the contrary, important relationships exist between the crust of the Earth, the Earth's interior and its external phenomena, and the geopotential fields.

The nature of some of these relationships is understood, but many of the links between these phenomena are poorly understood or completely unknown. It is a major goal to understand the exact nature of the relationships - to study the Earth as a complex planetary system and to formulate an Earth model which depicts the complex workings of this system.

3.1 EARTH DYNAMICS

The Earth Dynamics Program focuses its studies on both the interior of the Earth and the physical phenomena related to Earth rotational dynamics. Much of the information needed to study Earth dynamics is gleaned from data on crustal motion and the geopotential fields.

3.1.1 THE EARTH'S CORE

Seismology, which deals with the propagation of elastic waves through rock, can provide information on the nature of the Earth's interior (Figure 16). Study of seismic waves has confirmed the existence of a spherical core at the Earth's center and has added insight into its physical nature in the following way. These seismological results indicate the Earth's core has a radius of 3475 km, a little more than half of the Earth's total radius. The outer region of the core is composed of liquid iron of great density, under enormous pressure, and at a high temperature. Recent seismological evidence has revealed that the inner part of the core, with a radius of about 1215 km, behaves differently from the rest of the core. This behavior suggests a solid state, rather than the liquid state of the outer core.

3.1.2 THE MANTLE

Because the rigidity of rocks determines the velocity of seismic waves and because the velocity of these waves at various depths can be calculated from seismograms, it is possible to define the mechanical properties of the Earth's mantle.

In most of the Earth's mantle the speed of earthquake waves is so high that only a very rigid and dense rock, such as pyroxenite or dunite, will satisfy the observed conditions. For this reason the mantle is thought to be a zone of solid ultrabasic rock made up of magnesium iron silicate minerals. The mantle is about 2880 km thick.



Figure 16 - The Earth's interior

3.1.3 THE RHEOLOGY OF THE ASTHENOSPHERE

As early as 1914 Joseph Barrell, an American geologist, proposed that the plastic zone of the mantle be called the asthenosphere (from a Greek word meaning "weak"), to distinguish it from the overlying rigid zone, or lithosphere. The lower limit of the rigid zone represents not a change in rock composition, but instead a change in rheological properties. The lithosphere can be defined in several ways, but for the purpose of studying the motion and deformation of the tectonic plates, the rheological definition is usually the most appropriate. These studies represent an important link between the Earth interior and crustal dynamics.

The rheological properties of the asthenosphere have been deduced from crustal motions. This involves studies on how the stress exerted on plate boundaries is translated into earthquakes and how the sudden release of energy is propagated into the interior of the plate. The intermediate and deep focus earthquakes occur exclusively where portions of tectonic plates are subducted into the asthenosphere. Early seismologists proposed that earthquakes were caused by fault movements near the Earth's surface at depths down to approximately 55 km. In the 1920's a large number of seismic stations had begun work, and by 1930 it was clear that many shocks have a focus very much deeper. Those classified as having intermediate depth occur from 55 to 240 km down, whereas deep-focus earthquakes originate from 300 to 750 km. Below a depth of 750 km the forces that might tend to produce sudden fault slippage are apparently relieved by slow plastic flow of the rock and therefore cannot build up elastic strain to the point of rupture. Thus the Earth seems to have an outermost layer which has great strength, but which will break by faulting when unequal stresses are too strong; an underlying weak layer in which plastic flow or convection takes place, and a lower mantle which is also plastic but of apparently greater viscosity.

In the zone of deep-focus earthquakes, the rock is somewhat plastic, but if unequal stresses are suddenly applied it may snap like a brittle solid. Matter possessing these remarkable properties is described as an elastico-viscous substance--it can be brittle and plastic at the same time, depending on whether the forces that tend to deform it are applied suddenly and released, or applied steadily (as under the force of gravity).

The measurable parameter that describes asthenospheric rheology is usually viscosity. In general, the more viscous the asthenosphere is the more slowly the lithosphere moves. By measuring the deformation as a function of time, the effective viscosity and other mechanical properties of the asthenosphere can be estimated.

3.1.4 SOLID EARTH TIDES

Of considerable interest to geodynamics is the response of the solid Earth to tide-producing forces. Earth tides are detected by use of gravity measuring instruments at the Earth's surface. Measurements with gravimeters, which record minute variations in the force of gravity by the degree of stretching of a spring, have been made of the vertical component of the tide-producing forces. The observed spring movement is about two-thirds of the expected value because the Earth's crust itself rises and falls with the tide, changing the force of gravity and thus reducing the motion of the spring.

Investigations reported in 1970 showed that in the middle latitudes, at times of high Earth tide, a surface point on the crust is about 30 cm more distant from the Earth's center than at low Earth tide. Another important effect is the tilting of the crust near continental margins due to loading by tides in adjacent oceans.

3.1.5 POLAR MOTION AND EARTH ROTATION

The figure axis of the Earth (its direction of greatest moment of inertia) is misaligned with the Earth's angular momentum vector by a very small angle. This causes a motion or wobble of the instantaneous pole of rotation of the Earth, in addition to the well-understood astronomical precession and nutations. The motion of the instantaneous pole (abbreviated to "polar motion") is roughly in a circle a few tens of meters in diameter (Figure 17). The full period of this motion is about 432 days and is called the Chandler wobble after S. N. Chandler, the American astronomer who first described it in the late nineteenth century. The Chandler wobble would die away in a few years (due to the anelasticity of the Earth) unless it was continuously excited by dynamic phenomena within the Earth. The exact mechanism of excitation is still largely unknown.

Recently scientists have attempted to determine if there is a correlation between the occurrences of large earthquakes and changes in the Chandler wobble. Theoretical work has shown that earthquakes alone are probably insufficient to account for the excitation of the Chandler wobble, although there is a clear correlation on a time scale of a decade or so between the Chandler wobble and periods of volcanic activity and unusual numbers of large magnitude earthquakes.

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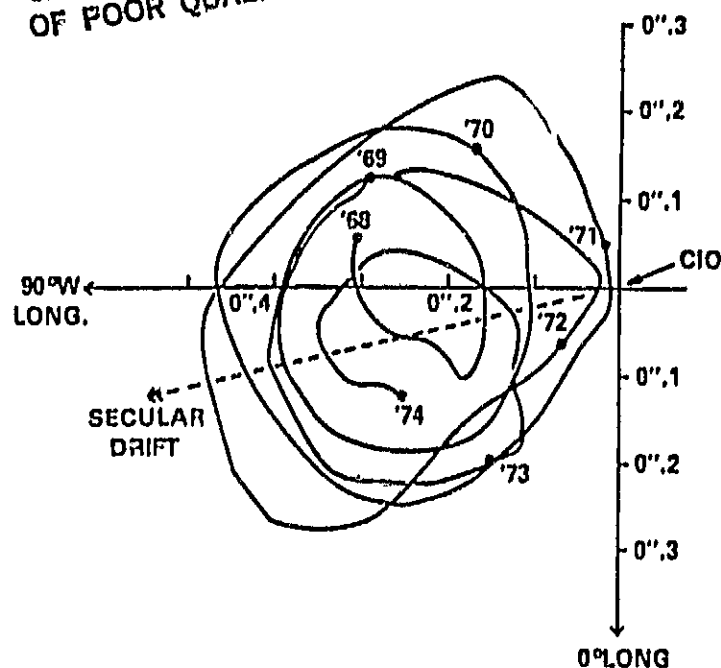


Figure 17 - Polar motion, 1968-1974

An annual component of polar motion is also observed, excited by seasonal movement of the atmosphere and oceans. In 1916, Sir Harold Jeffreys showed that the annual rising of sap in trees and the fall of leaves from trees, caused a very small annual effect on polar motion.

In addition to these and other longer-term variations of the Earth's rotation (some of which repeat every 18 or 100 years), the Earth's polar motion has irregular short-term changes. These are also suspected to be related in some way to large earthquakes. Up to the present, the accuracy of available astronomical techniques (about one meter) has not permitted detailed study of all of these questions. However, VLBI and laser ranging, which are about ten times more accurate than astronomical methods, are now providing new information for the study of polar motion.

The rate of rotation of the Earth is also continually changing, primarily due to the gravitational influence of the Moon. The Earth is slowing down because of tidal friction in shallow seas, and the day is becoming longer by a fraction of a second each year. This effect is fairly well understood and is easily adjusted for by scientists and engineers--for example, a "leap second" is inserted in the worldwide atomic time standard every year or so. What is not fully understood at present are small and irregular variations in length of day, amounting to a few thousandths of a second on time scales of a few days. This effect is thought to be due to interaction between the solid Earth and the atmosphere; and indeed new data acquired with satellite laser ranging now confirm that most of the effect is due to variations in the total angular momentum of the atmosphere.

3.2 CRUSTAL DYNAMICS

Historically geodynamics was concerned with the study of the internal and external phenomena of the Earth; but the processes which occurred on the surface of the Earth were generally thought to be unrelated to physical processes within the Earth. Today it is widely accepted that these processes are interrelated. Scientists from a variety of different disciplines have presented evidence which indicates that many of the processes which shape the crust of the Earth can be attributed to the response of the crustal rock to forces from within the Earth, forces which cause huge slabs of the crust to "drift" about the surface of the Earth. This unifying theory is called plate tectonics, and it provides a link between the dynamics of the crust and other Earth phenomena. With the wide acceptance of this theory, the science of geodynamics could be studied in a truly global framework.

Tectonics can be defined as the forces and movements that shape the surface of the Earth. According to plate tectonics theory the crust of the Earth is divided into a small number of thin and almost rigid spherical caps or plates that are moving horizontally with respect to one another (see Figure 18). The material of the plates consists of solid rock, and the region of the Earth that moves is known as the lithosphere. The lithosphere "slides" upon the partially molten upper mantle of the Earth, the asthenosphere.

The dividing zone between two plates is called a plate boundary. The boundaries of the lithospheric plates roughly correspond to the recorded epicenters of shallow focus earthquakes, indicating that plate boundaries are zones of localized seismic activity. There are three basic types of plate boundaries and each is associated with a distinctive kind of seismicity: mid-ocean ridges or spreading centers, trenches or subduction zones, and transform faults.

Although the most revealing differences between them are seismological, the three classes of plate boundaries are named for other characteristics (Figure 19). Ridges are named for their tendency to follow the crests of submarine mountain ranges. Ridges are diverging boundaries where new lithosphere is formed as the plates move away from the rift system. Also known as divergence zones, these types of plate boundaries are characterized by shallow-focus earthquakes associated with the volcanism along the mid-ocean ridges. Trenches or subduction zones, also known as convergence zones, are boundaries where cold and dense lithosphere is sinking back into the mantle. Trenches are accompanied by island arcs and active continental margins and are characterized by shallow, intermediate, and deep-focus seismicity along a plane associated with the subducted plate. Transform faults, which have more variable physiographic expression, are named for their structure. They are characterized by shallow-focus earthquakes with horizontal slips and may connect ends of an offset in a mid-ocean ridge or be a neutral boundary where two plates slide past each other horizontally. The San Andreas Fault System in California is a well known example.

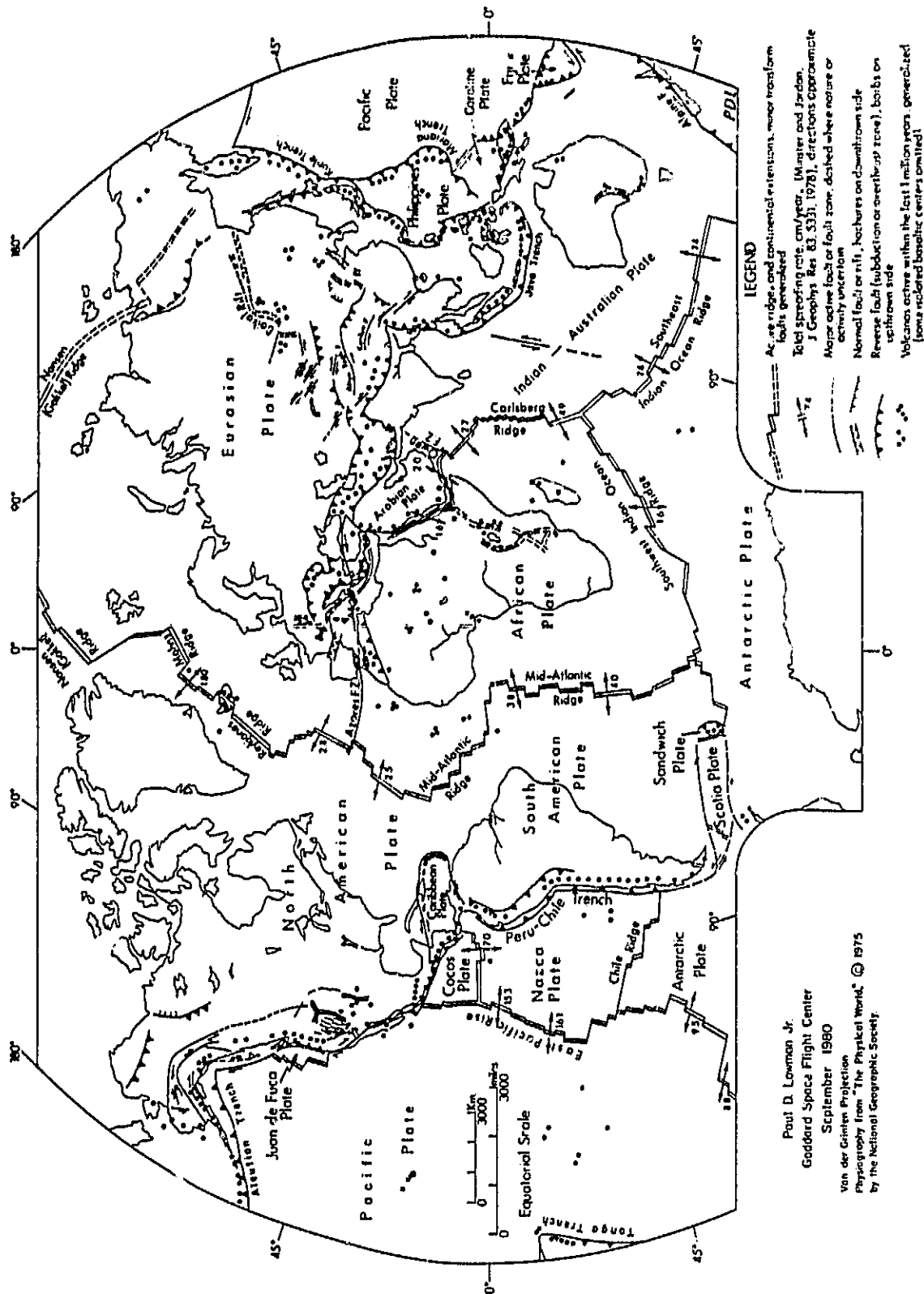


Figure 18 - Global tectonic and volcanic activity of the last one million years

Clues to when and how a surface feature was formed are found in iron-rich rocks, which become magnetized in the direction of the Earth's magnetic field at the time of their formation. Oceanic crust is formed when iron-rich lavas flow upward from the Earth's interior spreading centers. As the molten rock cools below the 600° to 700°C temperature range, the iron minerals become permanently aligned with geomagnetic field. The Earth's magnetic field, created by circulation of core materials, has reversed itself many times in the past at intervals on the order of 100,000 years, with each reversal probably taking a few thousand years. Ship-borne magnetometer surveys over the oceans have revealed a striped pattern corresponding to periods of normal or reversed magnetism.

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3.2.1 PHYSICAL PROPERTIES OF THE CRUST

The Earth's crust consists of a layer varying from 3 to 40 km in thickness. The crust averages 17 km in thickness when calculated as uniformly spread over the globe. The crust is distinguished from the mantle by the presence of a rather abrupt and clearly defined change in the velocity of seismic waves, indicating that there is a corresponding abrupt change in rigidity of the rock from crust to mantle.

The crust was defined on the basis of seismic data long before the development of plate tectonics, and the lack of exact correspondence between the seismically defined crust and the lithosphere (best defined as an outer thermal boundary layer) is still a matter of some concern to the few geologists who harbor reservations about the validity of plate tectonics.

The plates are not of uniform thickness; they range in thickness from an average of 60 to 70 kilometers under oceans and from 100 to 150 kilometers under continents. The plates tend to be internally rigid with most, but not all, of the deformation occurring at their edges by elastic bending or by brittle breaking. The deepest regions of the lithosphere, known as subduction zones, as illustrated in Figure 20 (after Dewey, 1979), veer into the upper mantle and deform plastically beginning at approximately 300 kilometers in depth and gaining increasingly more plastic behavior as they drop below this depth. In subduction zones the lithosphere extends to a depth of about 700 kilometers, at which time it is melted and re-absorbed into the mantle. Figure 20 is a highly simplified diagram of the subduction zone. Actually, the exact structure and nature of these areas are unknown.

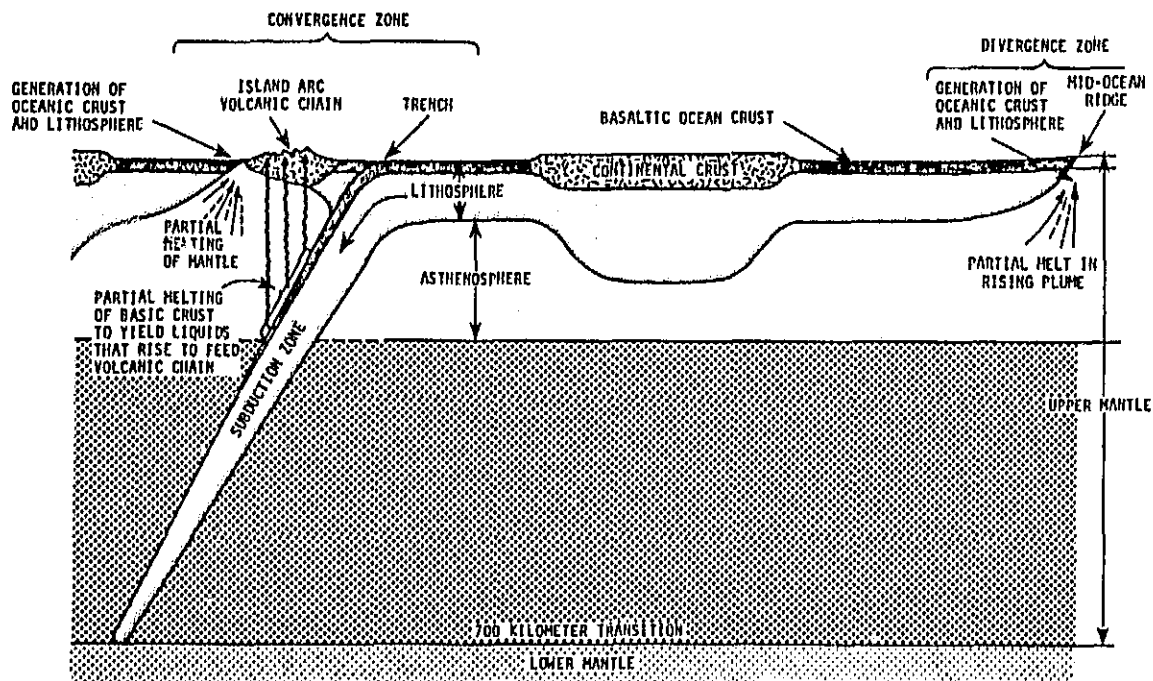


Figure 20 - Idealized diagram of a subduction zone

Seismology has provided the means to interpret the thickness and structure of the Earth's crust. Where an earthquake has a focus close to the surface and is located only a few hundred kilometers away from the seismograph station, the seismic waves do not penetrate the Earth more than about 60 km before they are gradually turned back toward the surface and reach the seismograph. Interpretation of the complex wave records reveals the velocities at which the waves traveled at different depths.

Generally speaking, rigidity of crust and mantle rocks increases with depth. It is known that longitudinal waves near the surface travel at about 6.2 km per second, which is expected in granitic rock, and that this velocity increases gradually or abruptly to the base of the crust, where it is about 7 km per second, a velocity expected in basaltic rock at this depth. At the boundary of crust and upper mantle, the velocity increases abruptly to more than 8 km per second, a speed to be expected of an ultra basic rock. Transverse waves undergo a corresponding velocity increase with depth. This surface of sudden increase in wave velocity, which separates the crust above from the mantle below is named the Mohorovicic discontinuity after the Yugoslav seismologist who first recognized the discontinuity in 1909 from the records of shallow-focus earthquakes. It has become accepted practice to designate this discontinuity as the Moho, or simply as the M-discontinuity.

At the margins of the continent the crust thins rapidly, and at the same time its base, marked by the M-discontinuity, becomes much shallower. The basaltic rock of the lower part of the continental plate extends out over the ocean basin floors as a basaltic layer 5 to 8 km thick. There is no granitic oceanic crust, only a varying thickness of sediment and the overlying water layer averaging 4 km in depth. The oceanic crust has all been created since the Jurassic Period by intrusion of molten mantle material at the oceanic ridges.

The present ocean basins are being created at divergence zones by spreading and recycled at convergence zones by subduction, on a time scale of about 200 million years, which is about 4 percent of the age of the Earth. Continents are mobile and permanent features. They are too buoyant to be subducted. They may be fragmented, moved, reassembled, deformed, and added to at continental margins, and eroded at their surfaces. Ancient continental rocks have been dated to have ages of 3.5 to 3.7 billion years.

3.2.2 PLATE DRIVING MECHANISMS AND MANTLE CONVECTION

At present, the most widely accepted theory for the driving mechanism that maintains plate motion is a form of thermal convection deriving its energy source from the initial heat that formed the proto-Earth and the heat produced by radioactive element decay distributed in the mantle (Figure 21). The questions of the distribution of the flow, the energy sources with respect to depth, and the nature of the lithospheric boundary layer are subjects of intensive current investigations. Because the lithosphere acts as a strong region in comparison with the less viscous asthenosphere, much of the discussion about the plate driving mechanisms is in terms of the effects of the substrata on the lithosphere or vice versa.

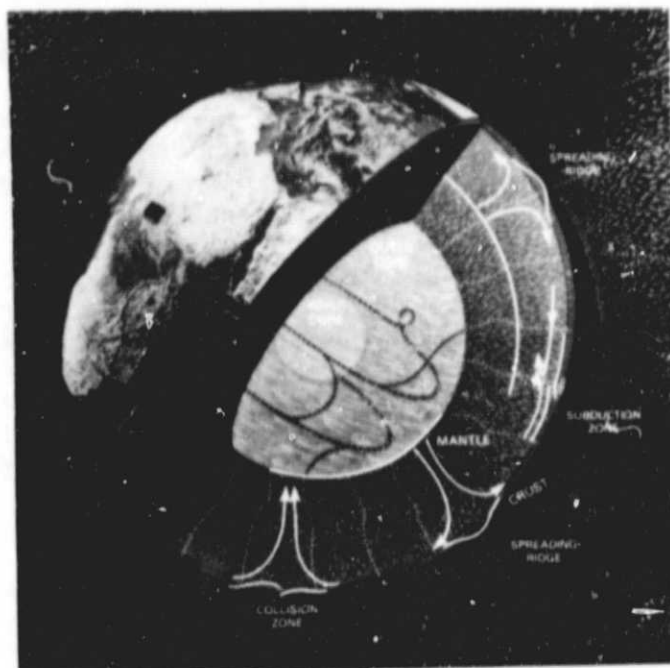


Figure 21 - Mantle convection

Other theorists believe the density contrast between the lithosphere and the asthenosphere is one of the primary plate driving mechanisms. At spreading boundaries, the thermally maintained topographic high found at submarine ridges provides a gravitational force that pushes the plate away from the ridge; this force is called the "ridge push." At zones of convergence the descending slab, colder and denser than the surrounding asthenosphere, is subducted pulling the plate along behind it. This force is referred to as "slab pull." Shear coupling at the base of the lithosphere is another force that acts on the plates.

Large scale mantle convection almost certainly exists. Studies have yielded evidence for convection on a scale where the convection cells would have a horizontal dimension comparable to their depth--about 700 km. Small scale convection may explain the flow of heat under old sections of oceanic plates and may also account for gravity anomalies in the ocean floor. Small-scale convection cells may also provide the rising plumes of magma, known as "hot spots", which create oceanic chains of volcanoes such as the Hawaiian Islands.

Further observations and measurements must be made before the validity of the mantle convection theories can be determined. Whether or not convection is a major component of the driving forces, shear stress at the base of the lithosphere must affect plate motion and deformation, as must the resisting forces at plate boundaries. The direct determination of present plate motion at various boundaries is crucial for evaluating the relative importance of the possible plate driving mechanisms.

3.2.3 INTERPLATE MOTION

The instantaneous motion of the plates with respect to one another can most easily be described in terms of the geometry of a sphere, where the plates are modeled as rigid spherical caps. A plate in motion over the asthenosphere occupies different positions at different times. By Euler's theorem the instantaneous relative change in position is described by angular motion about some line through the center of the Earth. This line is called the axis of rotation; and where it intersects the surface of the Earth, it defines the two poles of rotation. Furthermore, spherical geometry requires that all trajectories of relative motions be along small circles to the poles of rotation. These theoretical constraints are largely met by all of the criteria by which plate motions are demonstrated: sea floor paleo-magnetic anomaly "stripes" (described earlier) define spherical angles; velocities of separation of adjacent plates are constant in angle, but not linear in value. The direction of slip in earthquakes along plate boundaries, and the orientation of strike-slip faults that form or offset those boundaries, are in the small circle directions. This is the basic evidence for plate tectonics; that large pieces of the outer part of the Earth (plates) are rotating as quasi-rigid bodies with respect to the adjacent plates. The velocities of relative motion between adjacent plates range from about zero to about 18 cm per year as illustrated in Figure 22 (the Minster-Jordan Model AM1-2).



Figure 22 - Plate motion model

3.2.4 REGIONAL DEFORMATION

Regional deformation is a complex aspect of crustal dynamics. It involves the accumulation of strain as a result of the stresses applied by the tectonic forces, both along plate boundaries and within the plates. Faults, volcanism and earthquakes are manifestations of regional deformation.

Strain accumulation and plate deformation can be quite varied within one tectonic region. Geological structure responds to stress in a complex way that may not be constant in rate, appearance, or even location. Despite its ability to withstand great stress with only slight bending, or strain, a given rock has an elastic limit. If it is strained beyond this limit, either a fracture occurs and the deformed rock snaps suddenly back to its normal shape, or else the rock yields plastically and becomes permanently deformed.

If the rock fractures and exhibits some measureable offset as a result of shear stress, it will form a fault or shear zone. A fault is a planar discontinuity between blocks of rock that have been displaced with respect to one another in the plane of the discontinuity. A fault zone is a relatively narrow region containing many parallel or branching faults. A shear zone is a zone across which blocks of rock have been displaced in a fault-like manner, but without prominent development of visible faults. Shear zones are thus regions of localized ductile deformation, or they may consist of pervasively faulted rock - that is, a fault zone containing a very large number of closely spaced and branching fault surfaces.

The rock immediately above and below any nonvertical fault is referred to, respectively, as the hanging wall and the footwall of the fault. The displacement vector connecting originally contiguous points in the hanging wall and footwall is called the net slip. The components of the net slip parallel to the strike and dip of the fault are the strike slip and dip slip. A fault with dominantly strike-slip displacement is called a strike-slip fault, and a fault with dominantly dip-slip displacement is a dip-slip fault. Strike-slip faults usually have very steep or vertical dips and are then referred to as transcurrent faults or wrench faults. A large transcurrent fault connecting oceanic ridges, trenches, or triple junctions is called a transform fault.

The movement along faults may be translational or rotational. In translational movement there has been no rotation of the blocks relative to each other; all straight lines on opposite sides of the fault and outside the dislocated zone that were parallel before the displacement are parallel afterwards. Rotational movements are those in which some straight lines on opposite sides of the fault and outside the dislocated zone, parallel before the displacement, are no longer parallel afterwards.

Once the frictional bond or pressure holding together two sides of a fault is broken, the elastic strain energy, which may have accumulated over tens or hundreds of years, is suddenly released in the form of intense seismic vibrations, or earthquakes. An earthquake is an episodic event in which a fracture or rupture of brittle material in the Earth occurs, disturbing the mechanical equilibrium of the locality and emitting energy which radiates through the solid Earth as seismic waves. Near the epicenters of great earthquakes, these waves are responsible for the violent shaking of the ground that sometimes causes damage to buildings and other man-made construction.

Scientists have long been trying to predict earthquakes so that their devastating effects in populated areas may be reduced. Certain short-

range precursors of earthquakes have been observed: local changes in the propagation velocity of seismic waves; changes in the occurrence interval of small-magnitude seismic activity; foreshocks; changes in ground elevation, tilt or water levels; and radon gas concentration in water. Accurate long-range forecasting, (days of warning, rather than hours) is most valuable in terms of evacuating or warning densely populated areas. This type of forecasting utilizes statistical methods and long-term strain accumulation data. Unfortunately, the state of the art in earthquake forecasting has not yet allowed routine and accurate prediction of actual large magnitude events. Better understanding of the localized response to tectonic forces most probably will permit better prediction of these phenomena.

The relationship between strain accumulation and motion along faults does not always involve release of strain in a sudden, seismic movement. Strain may also be relieved on a somewhat steady basis in very small increments or at intermediate rates in a process referred to as creep, the slow deformation that results from long application of a stress. Of great scientific interest, particularly because of its ramifications on the understanding of earthquake processes, is the ability to recognize why certain regions may accumulate strain beyond the theoretical limits of creating an earthquake, why other areas along the same fault may release strain in sudden seismic events, and why other areas may distribute or release strain benignly.

Volcanism can also be an indicator of regional deformation. A volcano is formed only when magma (molten rock) generated from the crust or mantle is squeezed or extruded upward through fissures, cracks in the crust caused by structural weaknesses or faults. Most of today's active volcanoes are located in three narrow belts, namely the circum-Pacific belt, the belt along the ocean ridge systems, and the Alpine-Himalayan belt (Figure 23). The Alpine-Himalayan and the circum-Pacific belts lie in relatively curved segments, termed primary arcs, in which each arc is bowed convexly outward from the continental interior toward the ocean basins. The modern primary arcs are sites of intense tectonic activity. These mountain and island arcs are zones of crustal compression. The thermal energy generated by these disturbances in the crust and upper mantle causes the rock to melt. Volcanism also occurs along the mid-ocean ridges. This type of volcanism is a result of crustal extension.

The correlation between volcanic activity and tectonic activity is a topic of great interest to scientists. With the advent of plate tectonic theory, the taxonomy of volcanoes has been related to their tectonic setting. This has an added advantage by reducing the complex varieties of volcanoes to only one of three types: subduction zone volcanoes which occur in the plate margins of convergent zones; rift (or spreading center) volcanoes, along divergent boundaries; and hot-spot or mantle plume volcanoes that occur within the plates.

Using the tectonic-type taxonomy, the primary arcs are mostly subduction zone volcanoes. These comprise about 80 percent of all known active volcanoes. The mid-ocean ridges contain mostly rift volcanoes; they comprise about 15 percent of all known volcanoes (though this percentage may be higher if more information was known on the nature of submarine volcanic

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activity). Hot-spots are the least common and most highly disputed type of volcanic activity. The Hawaiian Islands and the volcanism in the Yellowstone Park region is attributed to hot-spot activity. But some scientists believe hot-spots to be more commonplace, occurring in regions of complex tectonism. Iceland, which is located in a rift zone, may be also the site of an active hot-spot. This may explain why it is not submerged like other parts of the Mid-Atlantic Ridge. The relationship between strain accumulation along a tectonic boundary, internal Earth processes and release in a localized volcanic eruption is rarely well defined. Elucidating this relationship may be the only way to give a long term accurate prediction to the time and place of an eruption.

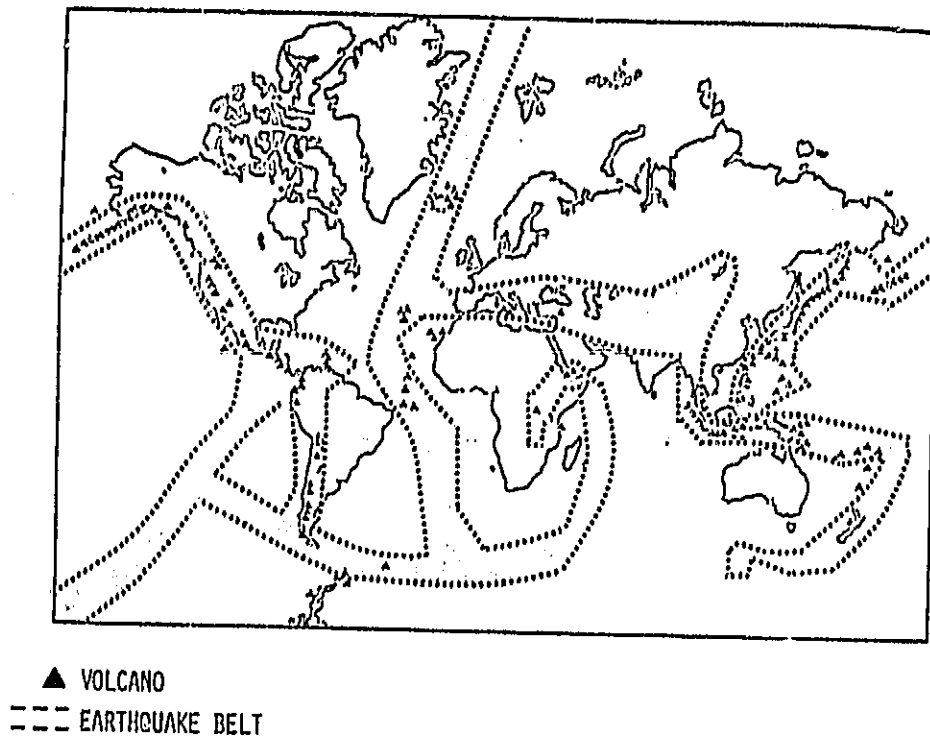


Figure 23 - Active volcanoes

The plate margins or boundaries are the most common sites for regional deformation. These areas are the direct recipients of tectonic stresses: compression when two plates collide, extension when they pull apart or separate, or a combination of the two along transform faults. The tectonic plates to some degree do behave as rigid blocks as almost all regional deformation occurs at plate boundaries. However, earthquakes, broad uplifts, and subsidence occurring in plate interiors are evidence of intraplate deformation. Intraplate deformation may be attributed to the nonrigid nature of plate interiors, or may indicate that deformation takes place in intracontinental zones of weaknesses; in some cases the plates are seen to contain smaller regions that move more or less as rigid bodies.

While the measurement of the global relative motion of the plates depends in part on the assumption that the plates are rigid and behave as single blocks, the assumption of complete rigidity is certainly not true at very local scales, as shown by intraplate seismicity and faulting. Whether individual plates are rigid at the level of their global motions or whether the deformation within plates is of a scale comparable to the interplate motions has yet to be determined.

3.3 GEOPOTENTIAL FIELDS

This section examines the scientific basis for the geopotential fields research. The geopotential fields that relate to the NASA Geodynamics Program are the Earth's gravity and magnetic fields.

3.3.1 EARTH GRAVITY FIELD

Gravitation is the force by which, due to their mass, all bodies attract each other. This force is directly proportional to the product of the masses of the bodies concerned and is inversely proportional to the square of the distance separating them and is expressed in terms of the acceleration it causes.

Because the Earth rotates, the normal acceleration of gravity differs with latitude. In an ideal homogenous spherical or ellipsoidal Earth, the value of gravity could be calculated if the latitude were known. However, gravity usually differs from the theoretical value because the Earth is heterogenous.

The gravity field can be measured by several techniques. Some of the gravitational methods, such as those using pendulums and gravimeters, measure the value of gravity directly. Other methods, such as those using torsion balances, measure the rate of change of gravity and the deviation of equipotential surfaces from a spherical shape.

When measuring the value of gravity directly, it is necessary to make a number of corrections to compare gravity measurements at adjacent stations. The "free air" correction accounts for the fact that above sea level, the force of gravity becomes progressively less as the altitude becomes greater. For all stations above sea level, therefore, a correction (+30.86 mgals per 100 meters) must be added proportional to the altitude.

Another correction is the Bouguer reduction. The rock between the measuring station and sea level increases the value of gravity, and the amount is proportional both to the altitude of the station and the density of the rocks between the station and sea level. The Bouguer reduction must be subtracted when one calculates the value of gravity at sea level. Thus, whereas the free air correction is positive, the Bouguer correction is negative; but the free air correction is the greater - approximately three times as large as the Bouguer correction.

Another correction is the terrain correction. Topographic features, such as hills and depressions, exert an influence on the measured value of gravity. This correction is particularly necessary when gravity is being

measured in an area of considerable topographic relief. The "isostatic" correction accounts for the fact that in most parts of the Earth the lithosphere is "floating" in hydrostatic equilibrium on the asthenosphere. For example, high mountains of low density rock have roots which depress the base of the lithosphere.

Gravity anomalies are calculated by determining the theoretical or normal value of gravity and, using the corrections for the observing stations, finding the difference between this corrected value of gravity and the normal value.

Relating gravity anomalies to plate tectonics has been of considerable interest. Probably the most systematically marked correlations of gravity anomalies with topography are the narrow negative anomalies found over ocean trenches and the broad positive anomalies over adjacent island arcs, marginal seas, and continental areas beyond them. The gravity irregularities associated with continent-continent collision belts are also being studied to determine the structure of the lithosphere in these regions.

On a global scale, there are some general correlations between the gravity field and features of the plate tectonic pattern, but this correlation is far from completely systematic. In principle, gravity anomalies provide one of the few significant constraints on deep mantle convection (along with the broad variations in topography, the plate velocities, and possibly certain systematics in isotope ratios), but the realization of this constraint requires global gravity measurements, of the kind that will be provided by the Geopotential Research Mission.

Progress in the scientific interpretation of the gravity field has been made in studies of the sub-oceanic structure. It is now generally understood that all the sub-oceanic crust and lithosphere have been created within the last 180 million years by seafloor spreading from ocean rises. The magnitudes and wavelengths of gravity anomalies have been used to infer the change in lithospheric thickness over time as a function of distance from the mid-ocean ridge and the variations in the rate and distance of deposition which are dependent on the spreading rate. Currently, attention is directed mainly to departures from standard models of a spreading and cooling lithosphere, with the hope of inferring the scale and nature of mantle convection.

In addition to calculating gravity anomalies, gravity measurements are used to relate the shape of the Earth to its gravity field. A geometrical representation of this field is the geoid, the equipotential surface of the gravity field of the Earth which most nearly coincides with the undisturbed surface of the oceans. It is the surface the seas would maintain if not subjected to tidal attraction of the Sun or Moon, waves, atmospheric disturbances, variations in water salinity, ocean circulation, and the Earth rotation.

The form of the geoid closely approximates an equipotential ellipsoid of revolution. Its polar radius is approximately 21.4 km shorter than the mean equatorial radius (6378.1 km). Its flattening, which is the difference

between the polar and equatorial radii divided by the equatorial radius, has been determined very accurately from satellite data (1/298.25), an improvement over the value previously known from the variation of the land-measured values of gravity from the equator to the pole. The history of gravity measurements from satellites is detailed in Section 2.5.

The smaller irregularities or radial differences between the geoidal and ellipsoidal surfaces (geoid undulations) seldom exceed 100 m and for most of the Earth are less than 25 m. However, these irregularities are highly important in geodetic leveling measurements and are significant indicators of internal stresses. Their interpretation is important for improving the accuracy of the geodetic results. Measuring system improvements are now in planning so that the very small irregularities in the geoid may be detected.

3.3.2 GEOMAGNETIC FIELD

The geomagnetic field is often represented by a simple dipole imbedded in the Earth, but it actually contains multi-pole components and is affected by complicated electric currents that flow in magnetospheric regions surrounding the Earth. The most accurate representation of the geomagnetic field is provided by a series of spherical harmonic functions. The field at the Earth's surface undergoes daily and other short-period variations which are caused by the electrical currents circulating in the ionosphere and which can be divided into two sorts--those with a steady daily cycle, or "quiet-day variation" and the larger, more variable ones called "storm-time variations" which may begin suddenly and diminish gradually over a period of about 48 hours. The quiet-day variations arise from the rotation of the main magnetic field in a sheath of ionized gas which maintains a constant orientation with respect to the Sun, while the storm-time variations are caused by the arrival of charged particles in the neighborhood of the Earth following solar flares.

Daily variations affect the measurement of the main geomagnetic field, and the short-period variations can be used to determine the electrical conductivity of the Earth. The main field also undergoes a slower variation which to a first approximation may be represented as a longitudinal rotation of the internal dipole with respect to the Earth. The study of this "secular variation" has illuminated the study of the origin of the main dipole field and is related to other geophysical phenomena as well, so that the description of the secular variation is a principal aim of the study of the magnetic field of the Earth.

The secular variation is a complex phenomenon, in which at least five components can be isolated at the present time. First is the decrease in the moment of the dipole field by approximately 5 parts in 10^4 per year. Early satellite data analyses indicate that a reverse in polarity may occur in the next one to two thousand years (Figure 24). Such magnetic field reversals are known to have occurred about every hundred thousand years in the recent geological past. These are responsible for the oceanic magnetic anomalies which are an important source of data on plate tectonic movements.

The second component of secular variation is the westward precessional rotation or drift of the dipole at about 0.05° in longitude per year. The third component is a decrease in the angle between the dipole axis toward the geographic axis of about 0.02° in latitude per year. The fourth component is the drift of the non-dipole field to the west at some 0.2° per year. Finally the fifth component is the growth and decay of features of the non-dipole field leading to fluctuations of some 10^{-8} nanotesla per year. Daily fluctuations in the geomagnetic field are produced by currents circulating outside the Earth in the ionosphere, but these are relatively small and have no bearing on the origin of the main field, which unambiguously is produced by sources inside the Earth.

The sources of the field do not lie within the outermost parts of the Earth, a possibility that had been suggested by the hypothesis of Lord Blackett that magnetization might be a fundamental property of rotating bodies. It seems clear that the origin of the main field and the secular variation must be sought in currents within the Earth, for the Curie points (temperature below which a substance ceases to exhibit any magnetic properties) of the known ferromagnetic constituents of the materials within the mantle are exceeded by the temperature within the Earth at very moderate depths, of the order of 20-30 km. Thus the study of the geomagnetic field can be separated into the low-order terms generated deep within the Earth, and the higher-order terms due to magnetic anomalies in the crust.

At the present time, the main field is thought to be generated by dynamo action within the core, that is to say, the motions of the electrically conductive liquid core relative to the magnetic field in the core generate currents which produce the magnetic field necessary to maintain them. Evidently, if this theory is valid, the electrical conductivity of the core must be great enough, the core must be liquid, and the viscosity of the liquid must not be too great. Since there is no other candidate theory for the origin of the geomagnetic field, it is usually supposed that the material of the core satisfies these conditions. There must also be a source of energy to drive the movement of the liquid against the viscous and electromagnetic forces that resist it. In the early part of the century it was first suggested that the magnetic field of a large liquid body could be maintained by dynamo action, but simulations showed that a very large class of motions could produce no field, namely those which were symmetrical about an axis of rotation. It was therefore thought that this ruled out the possibility of a dynamo mechanism for the origin of the magnetic field of the Earth, but it has now been shown that it should be possible to have a system of motions in the core of the Earth with sufficient asymmetry to give a self-maintained field; this theory is known as the theory of the self-exciting dynamo.

The geomagnetic field appears comet-like as viewed from space because of the continuous flow of plasma (or solar wind) from the Sun (Figure 25). This distortion demands the existence of a complicated set of currents flowing within the distorted magnetic field configuration called the magnetosphere. One major component of the magnetosphere is the Chapman-Ferraro or magnetopause current, caused by compression of the geomagnetic field by solar wind on the day side of the Earth, which results in a large scale current flowing across the field lines.

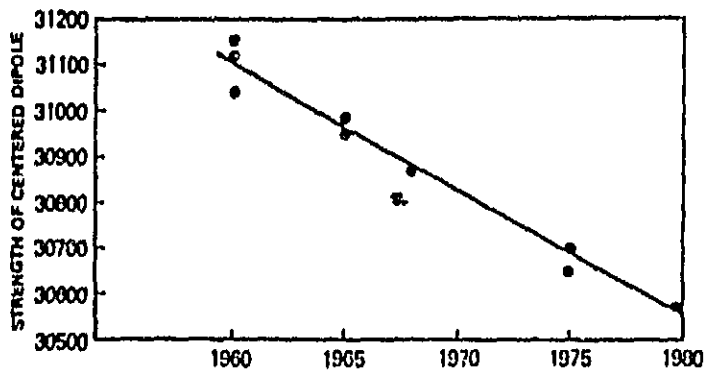


Figure 24 - Field decay

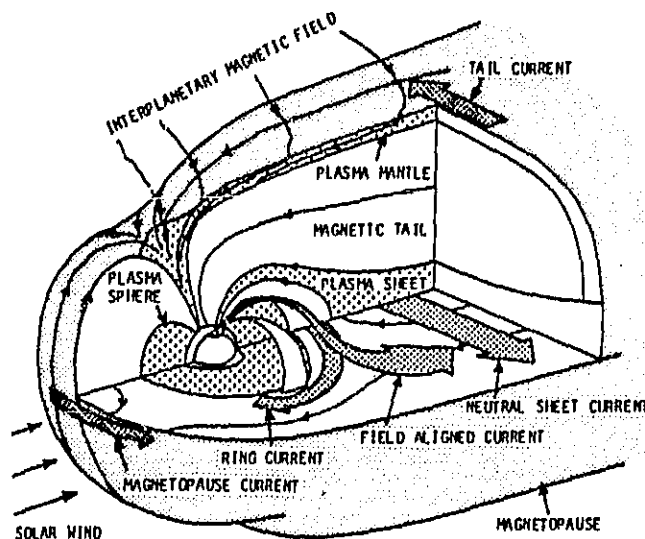


Figure 25 - The Earth's magnetosphere

The crustal magnetic field is the residual field that remains after the core (main field) and external fields (magnetosphere) have been subtracted from the measured field. This residual field is called the magnetic anomaly field.

Magnetic anomaly data are useful for regional studies of crustal structure and composition, the usefulness including possible correlation with the emplacement of natural resources and guidance for future resource exploration. The anomalies measured reflect such important geologic features as composition, temperature of rock formation, remanent magnetism, and geologic structure (faulting, subsidence, etc.) on a regional scale, therefore providing information on the broad structure of the Earth's crust. Magnetic anomaly maps based on aeromagnetic surveys are standard

tools for oil and mineral exploration and for basic research in crustal geophysics. Because of incomplete coverage, varying flight altitudes, and large temporal changes in background fields between the times when adjacent local surveys were made and when large local variations occurred, available aeromagnetic anomaly maps cannot effectively probe broad regional geological features. With the advent of the theory of plate tectonics, interest in identifying and mapping these broad regional features is increasing.

Characteristics of magnetic and gravity fields at and near the Earth's surface have been used to infer properties internal to the Earth. Combining satellite data with surface data from intervening times will permit more accurate analysis of the properties of the Earth. This information can be used to investigate changes of the fluid motions in the core that give rise to the magnetic field, properties of the core-mantle boundary that greatly affect fluid motions of the core, and transmission of this temporarily varying field through the lower mantle.

SECTION 4. TECHNIQUES OF GEODYNAMICS MEASUREMENTS

This section discusses the measurement techniques for observing and analyzing geodynamic phenomena. The science of geodesy is introduced, and conventional and space-derived methods and instruments are briefly covered.

4.1 INTRODUCTION TO GEODESY

The word "geodesy" is derived from the ancient Greek prefix "geo-" which means "the Earth" and the verb "daiein", to divide. Geodesy has thus come to identify the branch of applied mathematics and engineering concerned with measuring or determining the shape of the Earth or a large part of its surface, with precisely locating points on its surface, and with measurement of the Earth's gravity field. Rather than simply being regarded as a branch of applied mathematics, geodesy is quite properly considered as both an applied and a basic Earth science. As practiced today, geodesy is a subdiscipline of both geophysics and engineering, and it has applications to both the Moon and the planets in addition to the Earth. Historically, geodesy considered the solid Earth to be static; vertical position measurements were separated from horizontal position measurements. With recent scientific and technological developments, Earth measurements are possible in a three-dimensional time-varying space. Hence, the geodesists are learning how to deal with time-variant aspects of surface and subsurface features, while the geophysicists are learning more about the Earth's dynamic behavior from the interpretation of geodetic data.

4.1.1 MAJOR GOALS

The major goals of geodesy may be summarized as follows:

- a. Establish and maintain national and global three-dimensional geodetic control networks on land, recognizing the time-variant aspects of these networks;
- b. Measure and mathematically represent geodynamic phenomena, such as polar motion, Earth rotation, Earth tides, and crustal motion;
- c. Determine the gravity field of the Earth, including temporal variations.

These goals also extend to the oceans, the Moon, and the planets.

The geodetic networks of a country provide the control essential for its mapping and charting programs. Within the community of nations, it is important to maintain consistency between the geodetic networks covering a continent and even the entire Earth. The ultimate goal is a global geodetic system providing horizontal and vertical coordinates for national and international mapping and charting programs with the confidence that there will be no inconsistencies between the networks produced by individual countries. Closely related to the mapping responsibility is the

requirement for positioning the boundaries of countries, states, and smaller political subdivisions.

The Earth is continuously in dynamic motion and its dynamic behavior introduces another dimension to geodetic measurement - time. Technically significant rates are on the order of millimeters/year; to monitor these motions over significant distances is a real geodetic challenge. The task of maintaining accurate and up-to-date control networks is complicated by natural and man-induced changes in the Earth's crust. Continuous motions of up to meter amplitude occur as a result of solid-Earth tides, ocean tides, polar motion, Earth rotation variations, and other such phenomena. The establishment and maintenance of a reference frame within which the time-variant phenomena can be represented is one of the important geodetic activities for the near future.

The first two goals of geodesy relate to geometric "coordinates" that is, locating points and measuring baselines. A companion goal related to the physical aspects of geodesy is to determine the "shape" of the Earth from its gravity field. The shape of the Earth can be represented by the geoid. The improvements in mapping the smaller irregularities or radial differences between the geoid and the reference ellipsoid (geoid undulations) are essential for improving the accuracy of geodetic results.

4.1.2 CONVENTIONAL INSTRUMENTATION

The classical instruments of the surveyor and geodesist have not changed appreciably in recent years in terms of accuracy or use. They include the theodolite, zenith telescope, spirit levels, transits, and rods. The principles they employ are well known. In addition, electronic distance measuring and laser distance measuring have become standard in the last 20 years.

Electronic distance measuring employs the transmission of electromagnetic waves from an instrument to a reflector and back to the instrument; the distance between stations is determined by measuring the transit time or phase shift of the signal between stations. The instruments are usually categorized according to the emission source: microwave, infrared, and laser.

Strainmeters are used for crustal deformation measurements. They measure strain over short distances by monitoring changes in the length between two fiducial points compared with a standard length; the linear strain is simply the ratio of the change in distance to the standard. The measurement of the linear strain in three different directions fully determines the strain tensor. Strainmeters can be constructed using either a material standard or the wavelength of light to define the reference length against which strain in the earth is measured. A number of continuously recording instruments using either fused-silica tubes or invar wires under constant tension have been constructed. A few laser interferometer strainmeters with lengths of 30 m to 1 km have been operated, with an evacuated path provided between the end mirrors in order to remove atmospheric effects.

Tiltmeters measure changes in the relative height of two points separated by a known distance. A change in the tilt is simply the ratio of the change in the difference in height to the separation. For most phenomena associated with crustal deformations one expects the tilts and strains to be of the same order of magnitude. Pendulum tiltmeters mounted in boreholes are commonly used for measurements of irregular and secular tilt rates. Servo-controlled bubble instruments also have been developed. Long-baseline liquid tiltmeters provide measurements of tilt averaged over larger distances and are less sensitive to local effects due to rainfall, frost heaving, or nonuniform ground heating. They consist of two fluid reservoirs connected by a liquid-filled tube. The difference in apparent liquid level at the two ends usually is the quantity recorded.

Two methods are currently used for gravity measurement: free fall and force rebalance. The free-fall method determines absolute gravity by measuring accurately the time a proof mass carefully dropped in a vacuum takes to fall a known distance. Force balance instruments, such as gravimeters and conventional accelerometers measure the force necessary to support a proof mass in the gravity field. Because of the necessity of converting current or support geometry to force, these instruments measure relative rather than absolute gravity. The instrument may develop part or all of the force, the effect of the force, or a small deflection as gravity changes. Survey gravimeters are frequently corrected for drift by measurements at standard gravity stations. A small number of these stations have been calibrated by absolute gravity measurements using the free-fall method. Most gravimeters employ a mechanical spring in bending or torsion, but in one cryogenic instrument a ball is supported in a magnetic field produced by current in superconducting coils.

A gravity gradient implies a difference in gravity between two nearby locations. Gravity gradiometers measure this small difference by a variety of techniques and infer an average gradient. Each instrument determines one or two measurements of the five independent elements of the gradient tensor. At least five single-axis or three double-axis instruments are used together for a complete determination.

A large amount of present information on vertical crustal movements is based on spirit-leveling measurements. Concern about the reliability of the usually quoted accuracy for leveling has become apparent recently, particularly for regions of steep terrain and for older data. It has been noted that inaccurate rod calibration and failure to correct the historical data for vertical refraction may have produced systematic errors that must be taken into account when studying differences between levelings to determine crustal motion.

4.2 SPACE DERIVED TECHNIQUES

There are several types of geodynamics measurements that cannot be made utilizing conventional instrumentation and techniques.

Many of the problems in geodynamics are related to tectonic plate movement or deformation. Investigations in these areas depend on the ability to measure with a precision of a few centimeters the relative position and

movement of points on the Earth's surface, over distances up to thousands of kilometers.

Classical ground-based geodetic surveying methods, i.e., leveling and triangulation, are impractical for making measurements of station positions over distances greater than 100 km. Ground surveys must be made in a series of line-of-site measurements between points no more than a few tens of kilometers apart. The resulting accumulation of random and systematic errors soon brings the uncertainty in position above the required level. The best triangulation measurements are good to about 3 parts in 10^7 , thus the error exceeds 3 cm beyond about 100 km. The best leveling measurement accumulates similar random errors and systematic errors may be larger. In addition ground surveys are time consuming and expensive and therefore cannot be repeated often enough even in tectonically active areas.

Precise position determinations are made using the techniques of radio interferometry (primarily VLBI) and laser ranging (Figure 26). These techniques have demonstrated their ability to provide measurements over thousands of kilometers with accuracies of a few centimeters. Increased use of mobile equipment will allow frequent site visits to tectonically interesting areas. The reason why both of these techniques have been developed by NASA, rather than selecting only one method of determining positions, is that both laser ranging and VLBI have their respective limitations and systematic errors. Fortunately the systematic errors are different, and the results of intercomparisons of the data can be used to "remove" some of the effects of these errors.

Radio transmissions from satellites are also used for position determinations. Techniques using Doppler receivers are capable of providing positional information to a half meter or better. Newer receivers using signals from GPS have been demonstrated, experimentally, to have achieved positional accuracies equivalent to or better than conventional methods with only a fraction of the measurement effort. Studies show that the GPS receivers are capable of determining changes in baselines of several hundred kilometers to precisions of 1-2 centimeters.

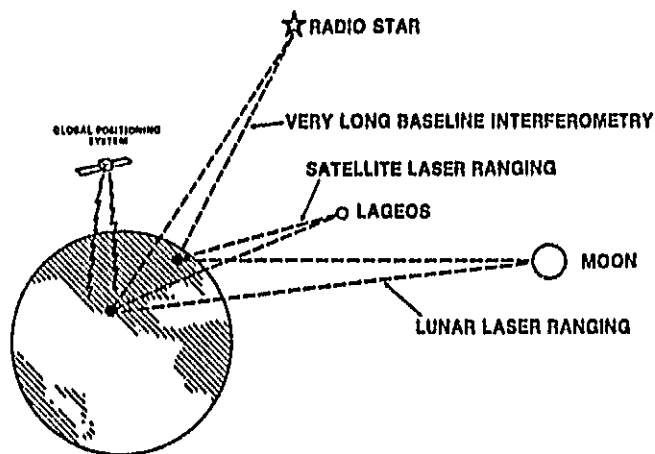


Figure 26 - Earth ranging techniques

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In order to derive the location of points on the Earth's surface from space data, it is necessary to know the orientation of the Earth. This is specified by the instantaneous pole position and universal time (UT1), both of which vary with time. Fortunately, this information is provided by the space techniques, since they depend on reference-points away from the Earth, and to an accuracy which is about an order of magnitude better than conventional optical observations.

Satellites are used to study the Earth's gravity field by observations, using ground tracking, of orbital perturbations; by in-orbit satellite-to-satellite tracking; by radar altimeter measurements of the ocean surface (after wave height is subtracted); and by gravity gradiometers in a single satellite.

There are large areas of the Earth's surface for which gravity anomalies are either unknown or known with low accuracy. For most of the world and even parts of the U.S., the gravity field is not known to better than 10 mgal (see Figure 27). Areas for which there is little information include Eurasia, much of Africa and South America, and the polar regions. Data do not exist for these areas because of political or topographical difficulties of access. Few of these difficulties are likely to be lessened in the foreseeable future utilizing conventional ground-based techniques. Satellite technology can, however, make it possible to obtain high resolution ($1\text{-}3\text{ mgal}$) data over a spatial area of $1^\circ \times 1^\circ$.

The use of satellite-borne magnetometers to map the Earth's magnetic field is relatively new. Earlier space measurements were primarily intended to study the near-Earth field to support space physics research. Satellite magnetic field surveying is now widely accepted as the principal means for global mapping of the field, for updating of magnetic charts and maps, and for studies of the field itself.

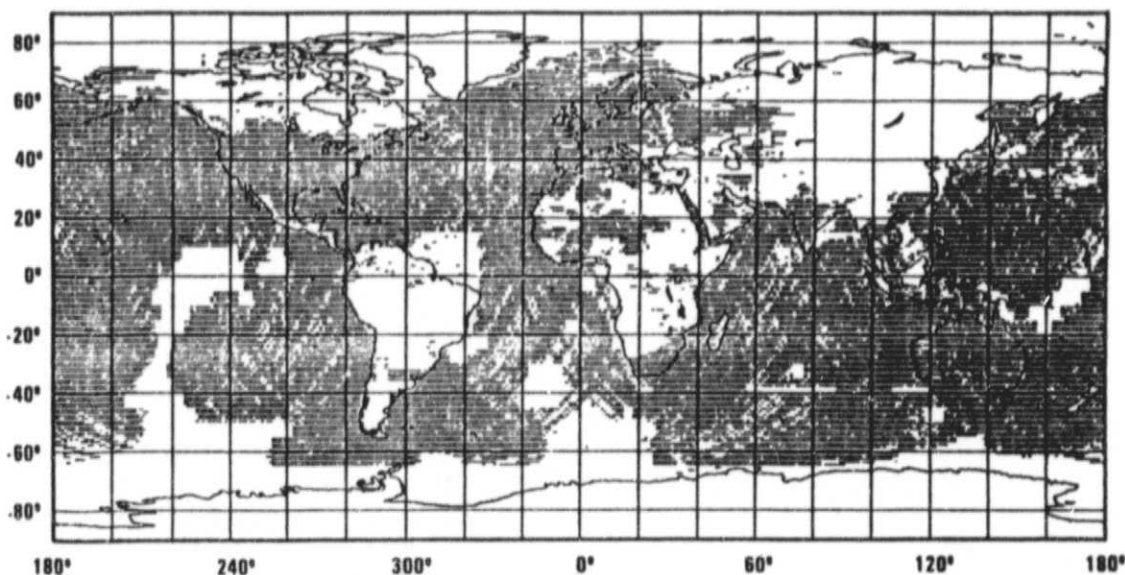


Figure 27 - $1^\circ \times 1^\circ$ Gravity anomalies (accuracy better than 10 mgal)

4.2.1 LASER RANGING

4.2.1.1 Methods of Measurement. A laser ranging station (Figure 28) consists of a laser, transmitting telescope and receiving telescope set up on either a permanent or temporary site at a location whose geodetic coordinates are known to a few meters. The laser is aimed towards a satellite equipped with optical cube corners on its Earth-viewing side which reflects back the incident laser pulse to the laser receiver located at the station. This process is controlled by the station computer which automatically starts and stops the laser firing and pulse counter. The laser firing is repeated at a rate of one pulse every few seconds. The pulse duration depends on the laser design and may vary from a few nanoseconds to a few hundred picoseconds. The distance from laser station to satellite is calculated using the measured one-way time interval and the velocity of light.

Though the process of laser ranging is simple in principle, there are many error sources which complicate the measurements. The laser transmits an optical pulse which does not have an exactly flat wavefront. Therefore the satellite does not uniformly intercept the full emitted signal; in fact, the exact portion and corresponding time that the pulse is intercepted is unknown. The reflect signal is also affected by the velocity of the satellite relative to the station. These result in a slight uncertainty in the position of the satellite. The uncertainty can be further complicated if the satellite is not well within the laser beam. The atmosphere poses another source of error; models must be used to estimate the signal propagation delays due to the atmosphere above the ranging site. Local meteorological conditions are monitored at the time of ranging and used as an input to these models.

The cube corner retroreflectors must also be uniform, and compensations must be made to account for the fact that they are not precisely equidistant from the laser transmitter. The location of the reflector must be known with respect to the center of mass of the satellite since it is this point whose motion is computed in the data analysis. This quantity, called the center of mass correction, is computed for each satellite, and if possible, measured prior to satellite launch. However, uncertainty in this correction may be a significant error source.

Receiver performance is limited by several factors. Just as in conventional radio frequency radar systems, the accuracy with which the pulse arrival time can be estimated is dependent on the pulse width and the signal to noise ratio. The electrons generated in the photodetection process are amplified by an electron multiplier, match-filtered, and detected by a discriminator. The electron multiplier introduces both random and systematic timing errors due to non-ideal electron optics and space charge effects. Optimal matched filtering is not feasible because of uncertainties in pulse shape and therefore some additional error growth is unavoidable. Electronic discriminators exhibit timing errors due to signal amplitude and pulse shape variations, as well as temperature variations. In addition to these effects, the electrical delay introduced by cables in the receiver will vary with physical configuration and temperature.

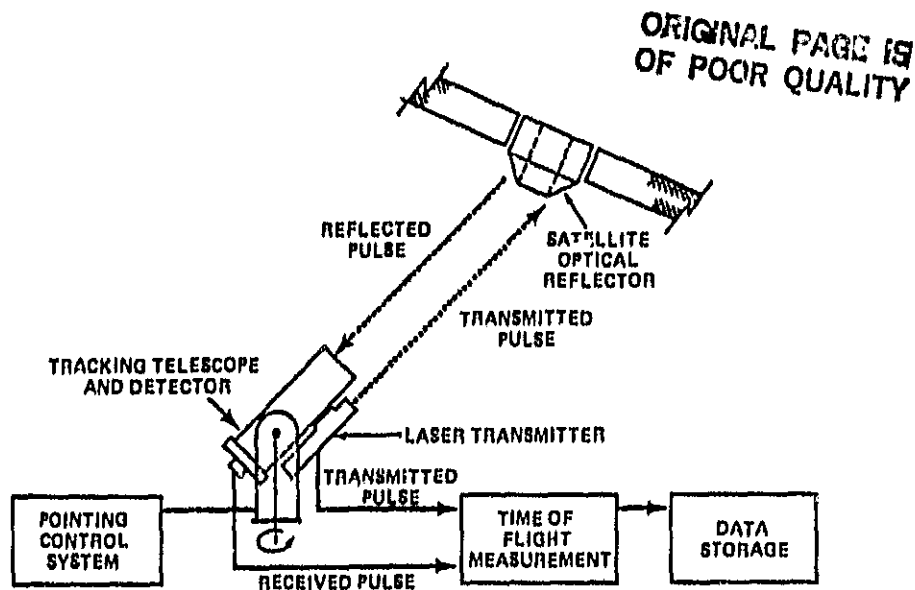


Figure 28 - Satellite laser ranging concept

Timing errors can be divided into two parts: the first part pertains to the accuracy of the time of flight measurement, and the second part relates to the "time-of-day" tag which must accompany the data so that they can be merged with data from other stations. The accuracy of the time interval measurement is dependent on the short-term and the long-term stability of the frequency standard used and is also dependent upon the resolution of the electronics within the time interval unit. Epoch is maintained using LORAN-C receivers.

In order to make the laser distance measurement accurate in an absolute sense, the system ranges to a ground target at a known distance prior to satellite tracking. Errors entered into the known distance through the limited accuracy of the local survey and the accuracy of the estimate of the atmospheric propagation delay used by the surveyor. After this known distance is established, the satellite laser system ranges to the calibration target and the mean value of these measurements is adjusted to agree with the known distance. Additional errors enter here due to instrument precision and atmospheric errors. Other error sources include physical shifts in the calibration distance with time and inaccuracies in the positioning of the ranging instrument with respect to the survey marker.

4.2.1.2 Lunar Laser Ranging. Most lunar laser ranging observations have been made at McDonald Observatory (in Fort Davis, Texas). McDonald Observatory uses its 107" telescope, the tenth largest astronomical telescope in the world. A separate 30" telescope facility at McDonald will soon replace the 107" operations, since technological advances no longer make it necessary to divert the large telescope for this purpose.

The Lunar Ranging Experiment (Lure) Observatory on Haleakala, Maui, is operated by the Institute for Astronomy of the University of Hawaii. It uses a 16" coelostat-configured telescope as a transmitter for pulses generated by a Nd:YAG laser system. Returns are received by the Lure-

scope, a novel type of telescope designed and constructed by the University of Colorado and the National Bureau of Standards. The Lurescope contains an array of 80 8" lenses (the optical equivalent of an 80" conventional telescope) mounted in a small rigid structure that can be guided entirely by computer. The lenses feed into a single photomultiplier.

The first returns from the Moon were acquired by Haleakala in August, 1976, and the observatory has been carrying out a program of checkout and calibration since that time. Along with its lunar ranging capabilities, modifications have been made to allow the 16" telescope to range to artificial satellites.

Lunar laser ranging stations are in various stages of development in several other countries: Orroval Valley (Australia), Dodaíra (Japan), Grasse (France), and Wettzell (West Germany).

The lunar laser ranging observations are two to three orders of magnitude more powerful than the previous optical methods for determining the position of the Moon, and corresponding improvements have been made in the lunar ephemeris. The lunar ranging data have been used to construct an ephemeris which gives the position of the Moon to within about 25 meters. This Lure-2 ephemeris models many effects which had not been previously incorporated into lunar theory, such as relativity, the lunar gravity field, and higher harmonics of the Earth's gravity field.

Work is now in progress to include smaller effects in the models, such as solid-body tides on the Moon and the interaction between the Earth's oblateness and the Sun.

The position of the reflectors on the Moon is known in selenocentric coordinates to about 25 meters, and the relative position of the reflectors to about half this amount. These positions are key control points in the lunar cartographic system.

4.2.1.3 Lageos. Lageos was launched in May, 1976 into a 5,900 km, circular, near-polar orbit. It is a 411 kilogram, 60 centimeter diameter aluminum sphere with a brass core, covered with 426 retroreflectors. Four retroreflectors are germanium, for use with infrared lasers and the remainder are fused silica for use with optical wavelength lasers.

The high altitude of the Lageos orbit combined with the satellite's spherical shape and large mass results in an extremely stable orbit. Laser stations have determined their position with respect to Lageos to a precision of a few cm. Using Lageos, stations in different parts of the Earth are able to measure their relative separations to similar precision. A series of measurements over a period of years will then enable determination of the movement of various ground station sites and hence, the tectonic plates on which they are located.

The Lageos orbit has been studied and models of the orbit show agreement with the laser data over a seven year period to better than a meter. In fact, a decay of the Lageos orbit has been detected and seems to be about 1 mm per day. Intercomparison studies which compared Lageos laser ranging to VLBI show good agreement with centimeter level accuracy.

4.2.1.4 Transportable Laser Ranging Stations. These systems represent the first efforts to develop high-performance, highly mobile laser ranging systems.

The TLRS-1 (see Figure 6), developed by the University of Texas, is designed to be able to operate without site preparation on any relatively level, firm surface. Mount orientation is determined by means of an electronic level and an azimuth marker, and by the observation of stellar sources. Automatic internal calibration methods are used. Sufficient computing capability is carried with the station so that daily communication with a home base is not required. Two centimeter accuracy has been achieved in certain tests. Best case accuracy is limited to about one cm by the atmospheric corrections and the measurement of system biases.

TLRS-2 (Figure 29) is a new transportable laser ranging station developed at Goddard Space Flight Center (GSFC). The TLRS-2 is designed to achieve centimeter-level ranging accuracy in a reliable, easy to operate system that may be readily transported in conventional aircraft. TLRS-2 contains a high performance laser ranging electronics system and computerized control system notable for its extremely compact dimensions. The ranging electronics, multi-stop event timer and system computer all fit into a single crate.

The new low-light level system is able to operate with single or multiphotoelectron pulses and with eight timing stops to enhance detection of the return signal. In order to insure a daytime Lageos tracking capability, an optical filter may be used in the receiver. The instrument is constructed in modular form and packed in four standard shipping containers (each measuring approximately one cubic meter). The four containers contain the laser and tracking mount, the operating electronics and computer, the timing system and test equipment, spare parts and auxiliaries. At the tracking site, the shipping containers become the environmental enclosure and operating area. The system operates at eye-safe power levels, and no aircraft radar is required. TLRS-2 is currently being tested at GSFC and readied for deployment to Easter Island.

TLRS-1 and -2 are expected to play significant roles in crustal dynamics studies. It is estimated that site occupation of one month should be sufficient to determine accurately any location relative to other Lageos observations. Thus a number of sites could be revisited on a biannual schedule so as to maintain their status as fundamental benchmarks.

4.2.2 VERY-LONG-BASELINE INTERFEROMETRY

4.2.2.1 Methods of Measurement. In VLBI, signals from extragalactic radio sources received at each of two or more ground stations are mixed with a reference signal from a high-quality local frequency standard and recorded. The difference between the respective instants of reception of a given wavefront from the extragalactic source at the two stations is derived. This time difference, estimated by cross-correlation of the two recordings, is equal to the difference in travel time of the signal to the two antennas, which is proportional to the projection of the baseline between the antennas onto the direction to the astronomical source, plus

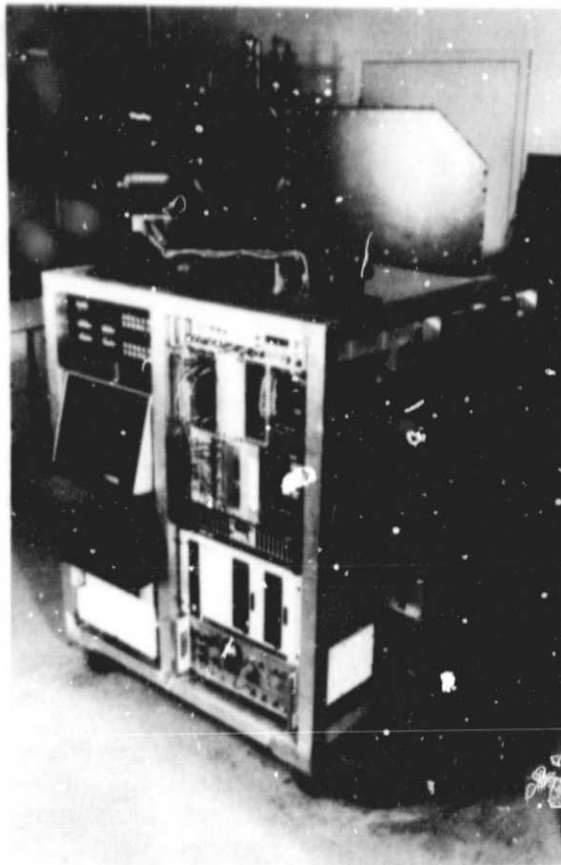


Figure 29 - TLRs-2

the clock synchronization difference. When signals from four or more sources whose directions are sufficiently different have been observed, the three components of the baseline vector and the clock difference can be derived.

These measurements are sensitive to the positions of the radio sources, the orientation of the Earth in an inertial reference system, and the movements of the crust caused by Earth tides and ocean loading. Model parameters for those effects are recovered in the least squares adjustment along with the baseline parameters. The observations are influenced by the Earth's ionosphere and troposphere, which affect the speed of the signals through those parts of the atmosphere. To some degree, these effects can be removed by calibration based on instruments at the observing sites.

The current precision of VLBI systems for position determination is 2 to 4 cm. Upgrading of the VLBI techniques is planned to achieve precisions of 1 or 2 cm. A key factor in achieving the performance is accurate correction for path length changes caused by water vapor in the atmosphere. Water vapor radiometers capable of reducing this error source to about 2 cm have been developed. Studies have been initiated to improve instrument calibration of atmospheric modeling to reduce the error to the 1 cm level.

4.2.2.2 Mobile VLBI Systems. The mobile VLBI systems include three stations (MV-1, -2, and -3) which are operated in conjunction with larger fixed-based stations. The three mobile stations, will be equipped to operate in a "standard" configuration by April 1983. That is, they will use a Mark-III recorder (112-Mb/s record rate) and will sample data across 400 MHz of bandwidth at X-band (8.4 GHz) and 100 MHz at S-band (2.3 GHz). The first two stations (MV-1 and -2), have measured data in other configurations since 1973 and 1980, respectively. The third station (MV-3) (Figure 30) has recently been fabricated. The MV-3 antenna van was ready for initial use in September 1982, and the MV-3 is to be operational in early 1983.

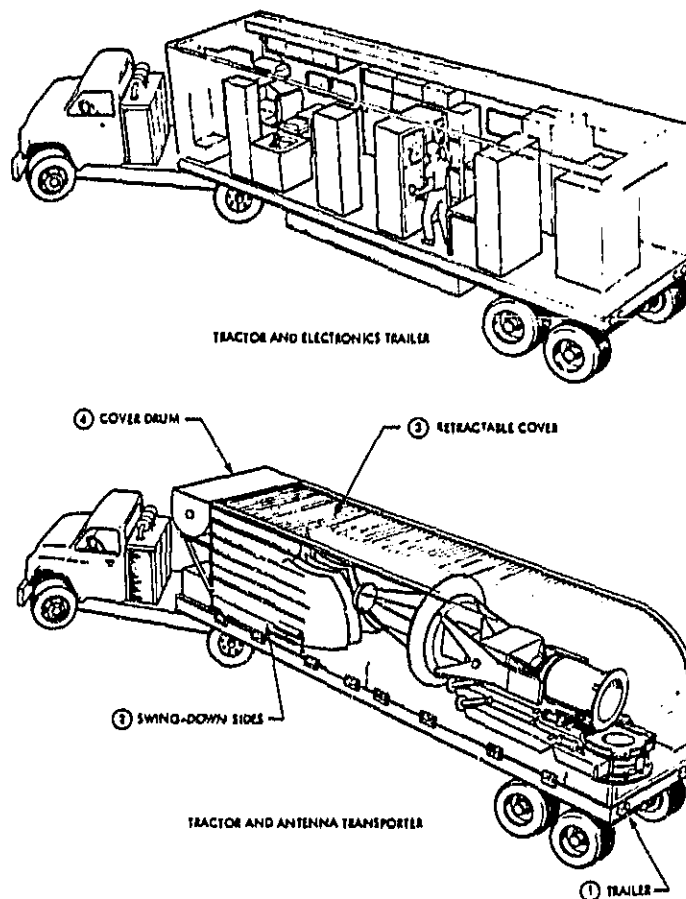


Figure 30 - Mobile VLBI station (MV-3)

The length of time a mobile station stays on site is determined by a trade-off between the probability of obtaining valid data and the cost of revisiting sites should the data be "lost." A 24 to 36-hour data acquisition period is currently used for MV-2, although good baseline solutions should be obtainable with six hours of data. Also, during the current phase of development, reliable baseline solutions seem to "require" three stations. (The solutions are based on forced closure of the triangle

defined by the three stations.) Theoretically, satisfactory results are obtainable with only two stations. The MV-3 design specification reflects the goal of obtaining a precise baseline measurement using a single base station and a six-hour data acquisition period.

The MV-2 station was designed to demonstrate higher mobility. Only eight hours are required for tear-down and set-up versus 14 days for MV-1. No crane or cherry picker is required. Although the MV-1 and MV-2 antennas (but not electronics vans) were obtained from U.S. Army surplus equipment, all MV-3 components were designed and built specifically for the Crustal Dynamics Project. The station is designed to be operated in the field by a two-person crew. A normal two-day operating cycle involves driving to a site, station deployment and checkout, taking six hours of data, tear-down, and preparation for driving to the next site. Engineering documentation is being provided with the MV-3, so that future stations can be manufactured from this design.

4.2.3 GLOBAL POSITIONING SYSTEM

The Global Positioning System (GPS) is being established by the Department of Defense in order to consolidate and improve present navigation systems. The system will include 18 satellites in six, twelve-hour circular orbits with an inclination of about 55° and an altitude of 20,000 km (Figure 31). Six satellites (Figure 32) with orbital inclinations of 63° were in orbit by mid-1980. The entire system is intended to be operational by 1988.

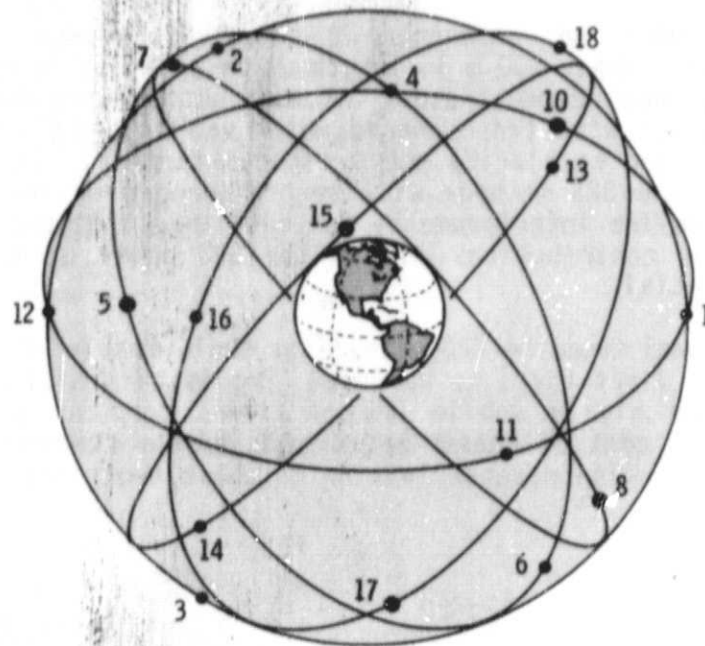
The signals transmitted to the Earth consist of biphase modulated spread spectrum signals. The signals are generated with a chirp frequency of 10.23 MHz and a different pseudo-random code for each satellite. Observations at both frequencies permit accurate corrections to be made for ionospheric effects. The accuracy goals for the system are 16 m in geocentric position and 3 cm/sec in velocity at the 90-percent confidence level for individual moving vehicles. However, much higher accuracy can be achieved for the relative positions of fixed stations separated by up to at least a few hundred kilometers.

Several concepts have been proposed for making use of the GPS signals to measure crustal movements. One method makes use of measurements of the phases of the "reconstructed carrier" signals, with knowledge of the original modulation code being used to generate these signals. A second method makes use of knowledge of the general structure of the code but not the code itself (Figure 33). The third method is analogous to the one used with astronomical radio interferometry but uses the GPS signals as the "noise" sources. No knowledge of the signal structure or the code is needed with this method.

Another interferometric approach has been investigated, which would involve placing small supplemental transmitters on future GPS satellites. This would permit considerable simplification in GPS receivers for geodetic uses and would avoid ambiguity problems. However, there are no current plans to add the necessary equipment to the satellites.

There are still many uncertainties, although the prospects seem good that all of the GPS methods being developed will achieve at least 3 cm accuracy

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SATELLITE 9 OBSCURED BY EARTH

Figure 31 - Global Positioning System

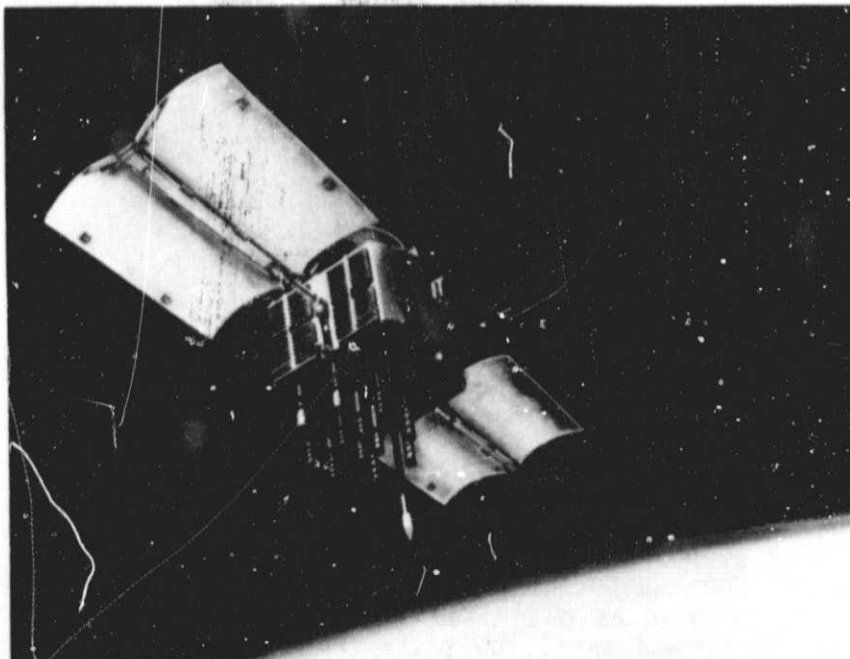


Figure 32 - GPS satellite

for the three baseline components at a high confidence level. For very short baselines, about 100 m in length, 1 cm accuracy in each of the three components has been demonstrated. A much better knowledge of the range errors associated with tropospheric water vapor in different regions may be needed in order to clarify the prospects further. It appears that at least some of the GPS methods will be preferred over the use of astronomical long-baseline interferometry for baselines that are short enough so that the error contributions due to the GPS orbit uncertainties do not become substantial.

The strong signal from the GPS satellites would enable very small antennas and short site visit times to be used. Preliminary studies indicate that very small and highly mobile GPS receivers can be built for a small fraction of the cost of quasar-based VLBI mobile stations, and should be able to make a position determination in about two hours.

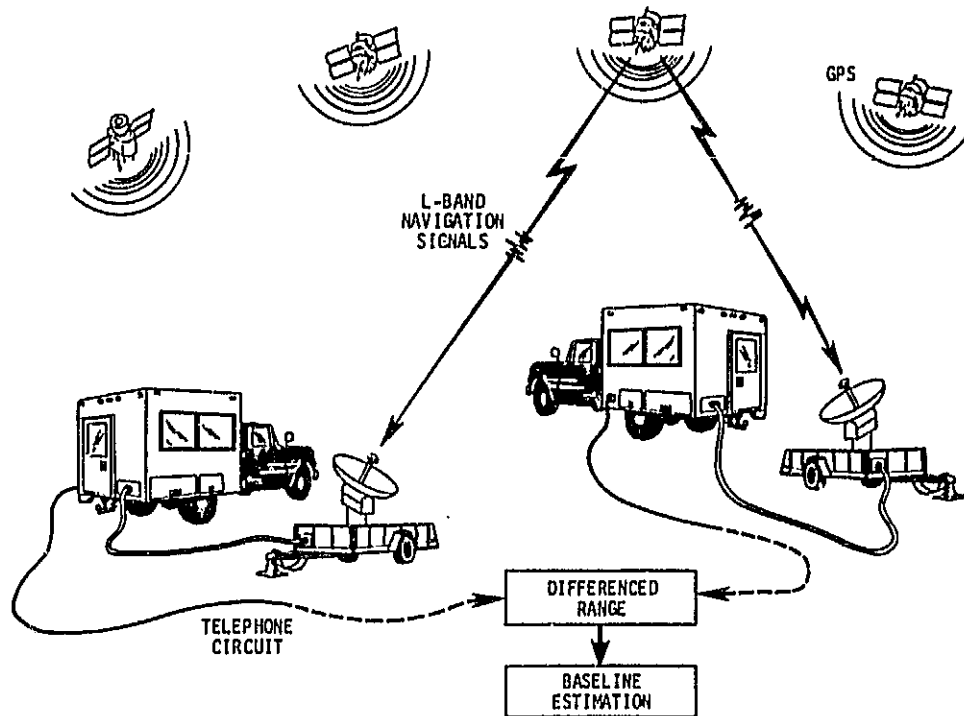


Figure 33 - GPS mobile receivers

4.2.4 SATELLITE GRAVITY MEASUREMENTS

Several satellite geophysical techniques are used to measure the Earth's gravity field and the equipotential surface (geoid) associated with mean sea level. The techniques discussed include radio Doppler, drag-free satellite technology, and satellite altimetry. It should be noted that tracking data acquired by laser ranging and satellite orbital studies also can be used to acquire data on the Earth's gravity field.

4.2.4.1 Radio Doppler. Range-rate tracking is based on the Doppler principle, which states that the change in frequency of a transmitted radio signal is proportional to the time derivative of the radial distance between the transmitter and receiver. If the relative range is decreasing with time, then the receiver frequency will be higher, when the range is increasing the frequency is lower.

With spaceborne transmitters the usual procedure is to count a fixed number of cycles of the Doppler frequency and record the required time interval. This procedure is repeated several times or done continuously while the satellite is above the ground station's horizon.

Similar techniques have been used to track one satellite by another (see Figure 13). The ATS 6 satellite-to-satellite tracking system used a single frequency of 2000 MHz. It is estimated to have a bias of 0.2 cm/sec and a noise of 0.04 cm/sec with 10-sec averaging. Several satellites have been tracked by ATS 6, although Apollo-Soyuz was the only one low enough to be sensitive to regional gravity variations.

GPS transmits a frequency pair in the gigahertz range, so that ionospheric refraction errors can be reduced to the centimeter level. It uses cesium atomic reference oscillators with frequency stabilities of one part in 10^{13} .

Further development of Doppler techniques is needed to measure the gravity field to a high resolution (10^{-10} or better) by satellite-to-satellite tracking. These techniques have been demonstrated in laboratory tests of two-way, coherent ranging at approximately 100 GHz which have produced range-rate accuracies of 0.03 microns per second. This latter technique is the basis for the gravity measurements planned with the Geopotential Research Mission (GRM).

4.2.4.2 Satellite Altimetry. The current state of the art in satellite altimetry takes the form of a microwave radar altimeter. Radar altimeters on GEOS 3 and Seasat have been used to detect dynamic ocean features, such as tides, waves, currents, etc., and to map mean ocean surface topography. This system, while limited to nadir viewing, provides accurate global mapping in the range of 5-10 centimeters for altitude and a few tens of centimeters for significant wave height. Plans are presently being developed to fly a radar altimeter as the primary research instrument on the Ocean Topography Experiment (Topex), the European Research Satellite (ERS 1), and other missions still in their conceptual phases.

A radar altimeter transmits a short burst of electromagnetic waves downward from the satellite; the reflected return signal is monitored by a fast-response instrument. The time of return is determined by a number of such pulses, and the results are added together. The resulting signal delay time and waveform shape are then used to determine the vertical distance from the wave source to the ocean surface and back to the detector. In determining this distance, a number of corrections must be made for atmospheric temperature and humidity, ionospheric activity, and ocean sea state. The sea surface derived from altimeter measurements includes the effects of the quasi-steady large scale ocean circulation which must be subtracted to obtain the "true" ocean geoid.

4.2.4.3 Drag-Free Satellite Technology. A drag-free system permits a spacecraft trajectory to be free of nongravitational forces such as atmospheric drag, solar radiation pressure, and Earth albedo (sunlight reflected by the Earth). The technique involves sensing the relative motion between the spacecraft and an unsupported proof mass internal to the spacecraft. Thrusters, operated by a control system, move the spacecraft to maintain the relative position of the spacecraft with respect to the proof mass. Since the proof mass is shielded by the satellite and therefore is free of disturbances due to surface forces, the spacecraft has the same drag-free orbit as the proof mass.

The Geopotential Research Mission will use a Disturbance Compensation System (DISCOS) where the motion of the ball relative to the satellite is sensed by capacitance pickups (Figure 34).

Drag-free satellites have been studied since the early 1960's by Stanford University and The Johns Hopkins University Applied Physics Laboratory. A U.S. Navy navigational satellite launched in 1972 was equipped with a DISCOS which proved the concept after 18 months of drag-free operation.

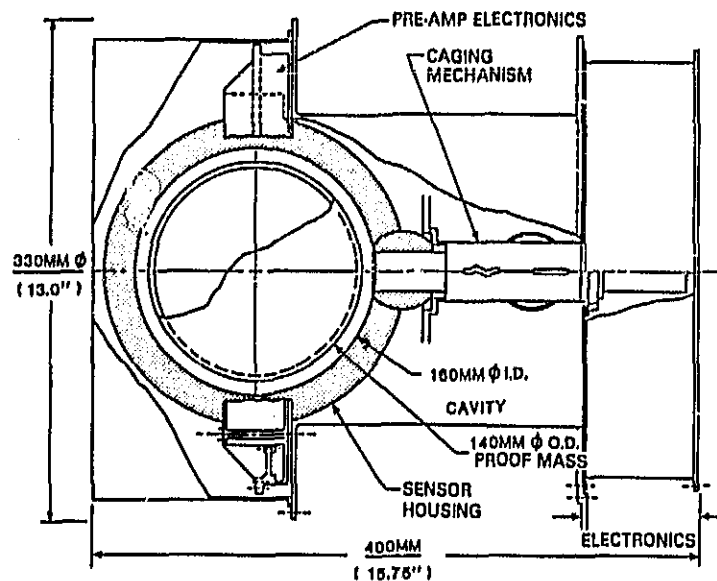


Figure 34 - GRM DISCOS sensor (140 mm proof mass)

4.2.5 MAGNETOMETER FIELD MEASUREMENTS

4.2.5.1 Measurement Methods. There are two basic types of magnetometers that have been used to measure the Earth's magnetic field from satellites. These are the fluxgate magnetometer which measures the direction as well as intensity of the field, and the alkali vapor magnetometer which measures intensity of field only.

In the fluxgate magnetometer a core of a high-permeability alloy is wound with two coils through which equal alternating currents are passed in

opposite directions, the currents being large enough that the magnetic fields they produce saturate the cores for most of a cycle. The whole core is wound with a single coil in which a voltage is induced by the changing flux. If the core is also subject to a steady field such as the Earth's, then there is a net positive or negative flux (according to the direction of the steady field) through the detector coil. The rate of change of this net flux is equal to the voltage induced in the detector coil and is characterized by the fact that it contains the second harmonic of the alternating inducing current.

In the scalar magnetometer, an isotope in vapor form is encapsulated in a cell. The vapor, either rubidium or cesium, (cesium-133 was used for the Magsat scalar magnetometer) is optically excited by a discharge lamp. The excited isotope atoms oscillate at a frequency depending on the magnitude of the magnetic field. Dual cells are generally used to account for changes in the measured field direction relative to the cell.

A potential source of error in satellite magnetic field measurements is in determining the absolute orientation of the sensors with respect to a reference coordinate system. In Magsat this effect was minimized by bonding two optical cubes to the sensor mount. They allow the sensor assembly to be rotated exactly 90° during calibrations to establish the absolute direction of the magnetic axes and later to reference the vector instrument measurements to the principal spacecraft coordinate system.

4.2.5.2 Magsat. The objectives of the Magsat mission were to study the Earth's magnetic field and magnetic anomalies associated with crustal inhomogeneities and to provide the USGS with data to be used in making magnetic field maps for the 1980 epoch.

Instruments aboard the Magsat spacecraft (see Figure 1) consisted of a dual-cell cesium vapor scalar magnetometer and a precision three-axis fluxgate vector magnetometer. Two star cameras and a precision Sun sensor provided information concerning the absolute orientation of the spacecraft in inertial space. Another system, the attitude transfer system, was used to determine the orientation of the sensor platform, located at the top of a 6m boom, with respect to a reference coordinate system on the spacecraft.

The two types of instruments flown onboard the spacecraft provided complementary information about the measured field. The scalar magnetometer measured the total magnetic field with an absolute accuracy that is determined by atomic constants. The precision vector magnetometer, on the other hand, measured the projection of the ambient field in three orthogonal directions with an absolute accuracy determined by calibrations with respect to a standard; thus they were subject to error and drift. Accuracy goals for the mission required a vector magnetometer, capable of measuring the ambient field with a maximum error of ± 1 part in 64,000 in magnitude and 5 arc-seconds in orientation.

Investigations using Magsat data were carried out in four areas of scientific interest: geomagnetic field modeling; crustal magnetic anomaly studies (i.e., postulating the crustal structure and composition that cause the magnetic anomalies); investigations of the inner Earth (the core, mantle, and core/mantle interface); and studies of external current systems.

SECTION 5. PROGRAM ACCOMPLISHMENTS AND PLANS

Since the current NASA Geodynamics Program began in the late 1970's, the investigations, missions and projects affiliated with the program have made numerous contributions to furthering the science of geodynamics. This section highlights some of the program accomplishments and the research plans for the next five to eight years.

For the past several years the NASA Geodynamics Program has supported research in federal laboratories, academic institutions, and private companies. The investigators and their investigations, including those supported through the Crustal Dynamics Project, the Lageos Project, the Magsat Project, and the Research and Technology Development Project have been grouped in three Program areas; Earth Dynamics, Crustal Dynamics, and Geopotential Research, and are listed in Appendices A, B, and C, respectively.

5.1 EARTH DYNAMICS PROGRAM

The area particularly emphasized by the Earth Dynamics Program (EDP) is the study of Earth rotation and polar motion. These studies utilize primarily VLBI, LLR, Lageos and Starlette orbital data, SLR, and Doppler space-derived data. In addition, sources such as BIH are used both as a study input and for intercomparison. Complex numerical models are often incorporated into these studies. Some investigators have related their research to structural studies and/or investigations of crustal motion or the Earth's geopotential fields. The investigators come from a variety of institutions in the U.S., from France, and from China.

Advances in understanding the Earth's core dynamics have been made under this program element, though much of the data utilized for core studies are magnetic field data from the Geopotential Research Program (GRP). Similarly, studies of the mantle utilize gravity data from the GRP.

A wider variety of EDP studies are categorized under the solid Earth tides and rheological studies element of this program area. The investigations often focus on one primary area or phenomenon which often may interface with CDP study areas, such as subduction zones, the crust/mantle interface zone, post-glacial isostatic rebound, mantle plumes, active plate margins, stress migration, Earth structural analyses, and continental "wakes". The studies involve measuring and modeling many of the dynamic phenomena associated with a particular region, or studying a particular phenomena and relating it to other phenomena or a specific area of the Earth. These investigators also represent a variety of domestic institutions and institutions from France and Spain.

5.1.1 EARTH DYNAMICS PROGRAM ACCOMPLISHMENTS

Several investigating teams have made progress in their determinations of polar motion and variations in Earth rotation rates. Results of the MERIT short campaign in 1980 (Section 5.1.2) have yielded baselines accurate to 2 to 3 cm, polar motion to 2 to 3 milliarcseconds, and UT1 to 20

microseconds. The Polaris stations have yielded baselines accurate to 2.2 cm (rms error). The results show significant short-period changes in polar motion and UT, indicating a need to perform such measurements on a daily, rather than weekly, basis.

Several groups are studying laser ranging data to determine polar motion and variations in the Earth's rotation rate. Polar motion and length of day have been estimated regularly from May 1976 to June 1981 (Figure 35).

Both long-arc and short-arc solutions for Lageos have been determined, and the results compared with BIH and Doppler solutions. The satellite laser ranging data compare favorably with the other solutions, particularly during the MERIT short campaign; differences of 0.02 arc seconds and 0.3 milliseconds in length of day are typical. Analysis of Lageos data shows a strong correlation between variation in angular momentum of the atmosphere and variation in length of day (Figure 36).

Lunar laser ranging (LLR) observations have led to estimates of Earth rotation variations and polar motion that closely agree to Doppler pole positions and BIH UTO. VLBI data acquired from 1972 to 1980 (which include the measurements from the MERIT campaign) show smooth changes of Earth orientation with small peak-to-peak variations over an interval of one week.

Both SLR and LLR data have been used to calculate the product of the gravitational constant and the mass of the Earth (GM). The GM value derived from LLR is a standard adopted by the IUGG and used in studies of polar motion and Earth rotation. LLR provides a method for estimating possible changes in the gravitational constant, but attempts to calculate this quantity from existing data have been inconclusive. Acquisition of further data will help to establish reasonable bounds on this important quantity.

An important geophysical quantity is the secular acceleration of the longitude of the Moon caused by tidal dissipation in the Earth, which controls the slowing down of rotation of the Earth. This quantity provides information on the phase of the major tidal components and puts bounds on the bulk anelasticity of the Earth at very long periods. Lunar laser ranging has given additional very precise determinations of the secular acceleration of the longitude of the Moon, -24.6 ± 1.6 arc seconds per century per century by one team of investigators and -23.8 ± 4 by another investigator. Further observations will result in significant refinement of the accuracy of this figure.

Lageos data have been used to expand the model of amplitudes and phases of six major solid Earth and ocean tidal constituents. Locations of 25 laser tracking stations around the world can now be estimated with average precision of about 25 cm.

Models developed by Earth Dynamics Program investigators continue to produce increasingly more accurate descriptions of Earth rotation, variations such as the Chandler wobble, and the effects of tides and atmospheric angular momentum on the motion of the Earth. An accurate

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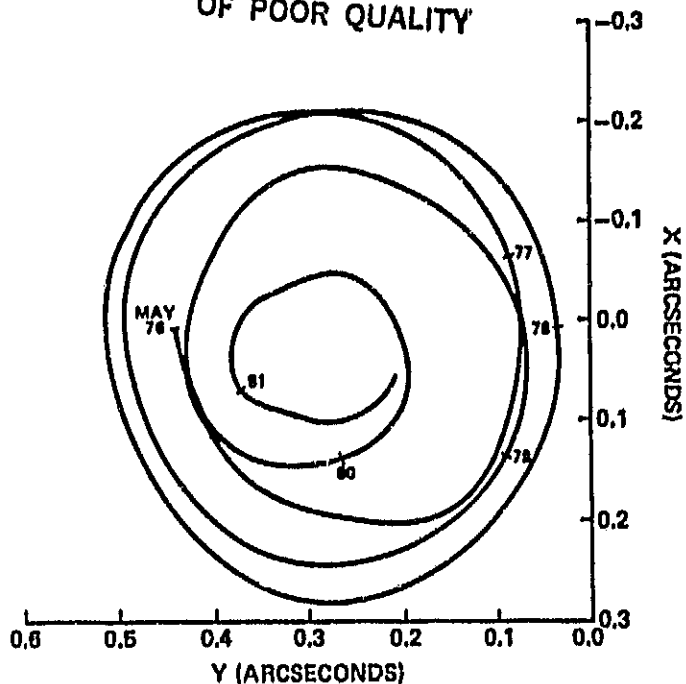


Figure 35 - LAGEOS polar motion measurements

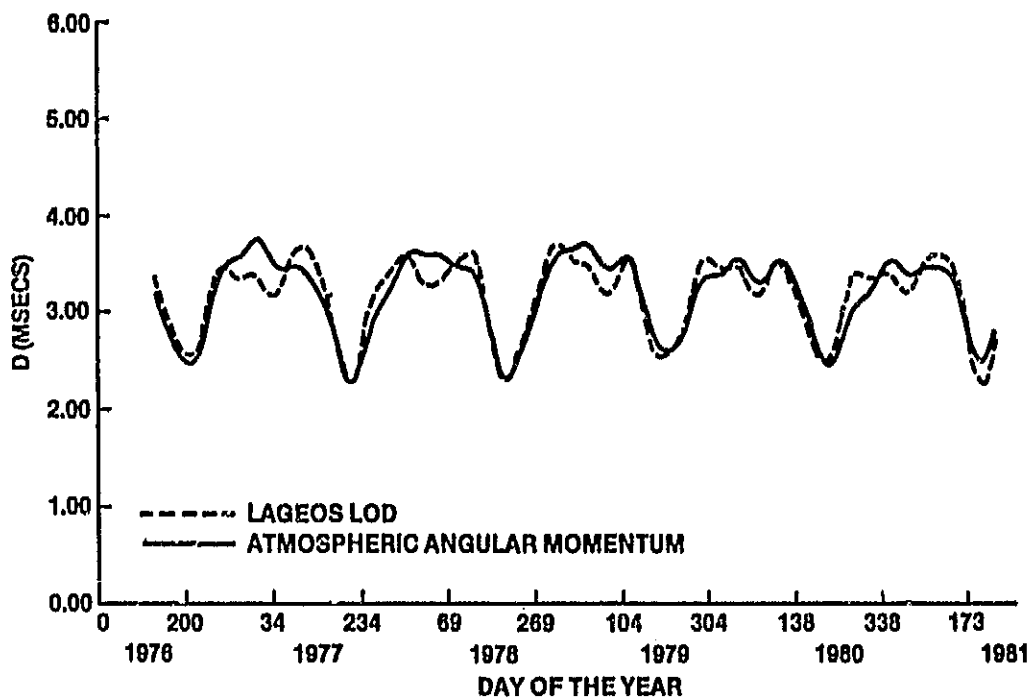


Figure 36 - Comparison of atmospheric angular momentum with
LAGEOS variations in length of day (LOD)

description of the elastic-gravitational deformation of a rotating, slightly elliptical Earth subject to external gravitational forces has been developed

Theoretical estimates of the Chandler period, accounting for the Earth's slightly non-hydrostatic equilibrium shape, have been refined and have produced the first valid estimate of Chandler damping caused by anelasticity in the mantle and crust. These results served to significantly tighten bounds on the allowable frequency dependence of anelasticity over the period range of one hour to fourteen months.

The complex interactions of pressure, gravity, and the magnetic field in the core may influence the dynamical motion of the Earth. Core effects have been taken into account in computing corrections in the amplitude of the 18.6 year nutation obliquity of the Earth.

Results of studies of the internal dynamics of the Earth have led to new models of mantle convection. These models show that when both the top and bottom boundaries of varying temperature and viscosity are stress-free, the cold high-viscosity top thermal boundary layer has a dramatic effect on the cell aspect ratio and vertical convective flow structure. The precise manner in which the shallow high-viscosity layer is stripped off may critically affect model results, so that viscosity variations across the top thermal boundary layer may result in significant differences between the interior temperature, surface deformation, and gravity anomalies associated with constant and variable viscosity convection. Another model which describes the rheological conditions of the asthenosphere has been used to predict plate motion and the propagation of stress following an earthquake. Several investigators are working on understanding relationships between internal Earth structure and crustal dynamics. One area of interest is the dynamics of converging boundaries or subduction zones. Residual geoid anomaly profiles for island arcs are being used to constrain numerical models of flow and temperature in subduction zones with a view to obtaining a better understanding of the deep structure of these regions and to address the question of the depth to which the return flow extends. Initial results obtained using a simple Newtonian model show a broad zone of downwelling centered on the trench and predict geoid anomalies an order of magnitude larger than those actually observed.

A gravity low south of India has been correlated to the existence of a "continental wake" due to the lithosphere in this region moving over the asthenosphere. Geoid lows and anomalously shallow sea floor occurring behind drifting continents are also found southwest of Australia and east of North and South America; these may also be continental wake phenomena. Several differences occur between the oceanic and continental upper mantle (viscosity, composition and lithospheric thickness) that may be important for creating continental wakes; continental tilting and shedding of high-density mantle are probably not important. Less dense mantle rising in the wake of the continent would produce geoid and topographic highs if the mantle beneath the oceanic lithosphere behind the continent were of uniform viscosity. However, if a zone of low viscosity beneath the oceanic plate reduces the normal stress on the base of the lithosphere and the

resulting uncompensated topography, a geoid low may occur in association with a topographic high, as observed in continental wakes.

Specific regions have been studied and applied to rheological models, and these are described in Section 5.2.2.

5.1.2 EARTH DYNAMICS PROGRAM PLANS

A program of international cooperation in studies of Earth rotation sponsored by the International Astronomical Union (IAU) is planned for the 1980's. The program is called Monitoring of Earth Rotation and Inter-comparison of the Techniques of observation and analysis (Project MERIT). The objectives of MERIT are:

- a. To foster the development of new techniques for the measurement of the variations in the rate and axis of rotation of the Earth.
- b. To obtain precise data on Earth rotation in order to increase understanding of the causes and effects of the variations.
- c. To make recommendations on the observational basis and organizational arrangements for future international services on Earth rotation.

An initial period of observations to test techniques and arrangements for international cooperation occurred from September to November, 1980. During this period, the MERIT short campaign, special efforts were made by NASA and other organizations to acquire laser and VLBI observations of polar motion and Earth rotation and to accelerate the processing of data. The MERIT main campaign will commence in September 1983 and extend to November 1984.

Another cooperative program for Earth rotation and polar motion, Polaris, was initiated in the late 1970's by NOAA and NASA. Polaris will produce Earth rotation and polar motion determinations utilizing three primary VLBI stations, with cooperation from a few back-up stations. The stations were selected using three basic criteria: to make maximum use of existing facilities, to place the stations on stable parts of the North American continent, and to allow for multiple use. The stations are located at Westford, Massachusetts; Fort Davis, Texas; and Richmond, Florida.

The planned NOAA Polaris network of three stations (Figure 37) will carry out determinations of Earth rotation and polar motion with an angular precision of 0.002 arc seconds. As checks to account for possible plate motion, periodic co-observation will be made between the Polaris stations and VLBI stations on other plates.

NOAA began interim testing of the Polaris network in November 1980 using the Fort Davis station and the Haystack station (substituting for Westford) to obtain twelve hours of observations once every two weeks. The Onsala, Sweden, station is participating on an "as available" basis, normally about once per month. In 1981, routine observations for one 24 hour period every other week were initiated using Fort Davis and Westford.

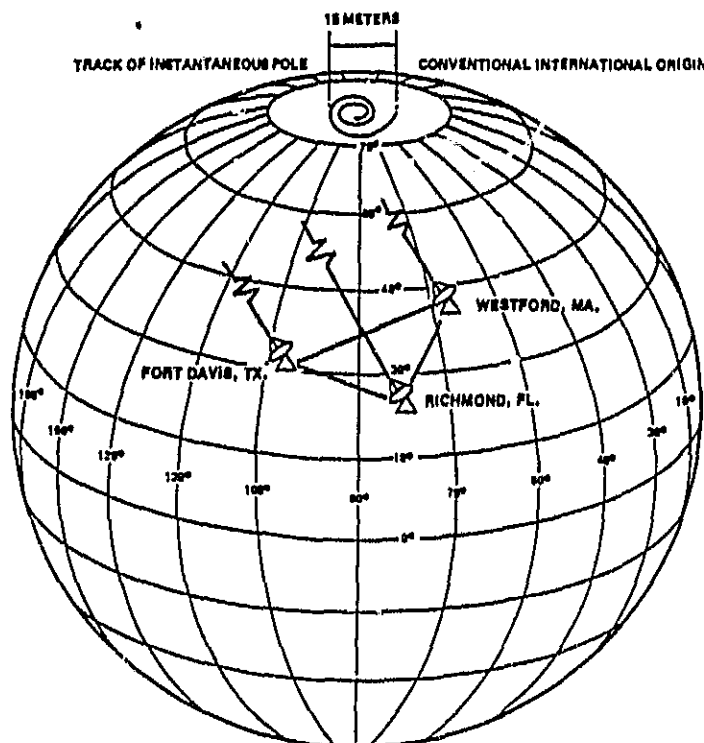


Figure 37 - Polaris network

The Richmond station is to be completed in 1984, but will initiate operations in September 1983 using systems provided by NASA.

LLR station improvements currently underway are expected to result in a reduction in ranging error from 9 cm to 3 cm. The McDonald Laser Ranging Station is in the final test phase. The lunar laser ranging station at Orroval Valley, Australia, is being upgraded through a cooperative effort involving NASA and the Australian National Mapping Division. This station, the Natmap Laser Ranging Station (NLRS), is expected to be operational by early 1984. The lunar laser ranging station at Haleakala, Hawaii, is expected to be operational in early 1983. The combination of three stations, each with improved performance, should result in significant scientific advances in studies of both the Earth and the Moon.

5.2 CRUSTAL DYNAMICS PROGRAM

The Crustal Dynamics Program was initiated to address the need for new information regarding the nature and mechanics of earthquakes and related crustal processes. The Program will provide a strong scientific foundation for eventually determining the time and location of major earthquakes. The Program also addresses the need for better methods of maintaining national networks of geodetic control by applying procedures for monitoring crustal motion.

Plate motion provides the input forces which lead to earthquake occurrence. More information is needed to determine the driving forces

that move the plates, whether plate motion is smooth or episodic, what the present relative velocities of the plates are, whether the plates behave as ideal rigid bodies, whether there is deformation internal to the plates, and whether internal deformation accounts for a jerky behavior of plate motion or for earthquakes internal to plates. The magnitude of the crustal movement and deformation is small, varying from a few millimeters per year in the interior of some plates to about 18 centimeters per year for the total motion of the fastest moving plates. In order to answer many of these questions, observations covering much of the Earth's surface taken over periods of decades will be needed. Also directly related to this Program, are elements of the Earth Dynamics Program, such as short-term variations in polar motion, variations in the Earth's rotational rate, and studies linking the dynamics of the Earth's interior to crustal motion.

The Crustal Dynamics Program recognizes the need for an organized effort within the program in order for advances to be made in the areas of crustal dynamics and earthquake mechanisms. The Crustal Dynamics Project fulfills this need.

The following section examines the objectives and plans for the Crustal Dynamics Project.

5.2.1 THE CRUSTAL DYNAMICS PROJECT

The Crustal Dynamics Project was established by NASA in 1980 to apply space technology to advance the scientific understanding of crustal movement and deformation and earthquake mechanisms. It is managed through the Goddard Space Flight Center.

The objectives of the Project are to measure and model: regional deformation and strain changes related to earthquakes at the plate boundary in the Western U.S. and Alaska; the present relative velocity of major plates, with emphasis on the North American and Pacific Plates and those plates interacting with the Pacific Plate; internal deformation of the North American and Pacific Plates; and regional deformation in regions whose tectonic setting is similar to that of the Western U.S. and Alaska.

The measurement techniques used and being developed by the Project include SLR, LLR, and VLBI. The Project uses both fixed and mobile stations. The locations of the fixed stations including cooperating stations in other countries are given in Table 2. The Project data products include positions of the observing sites as a function of time, baseline lengths and baseline directions between stations as a function of time, and values of polar motion and Earth rotation. The accuracies expected to be achieved vary with the observing site and measurement technique used, but precisions of a few centimeters over baselines of up to several thousand kilometers, and baseline length changes of one to two centimeters per year, are expected to be obtained over the lifetime of the Project (through 1988).

The Crustal Dynamics Project is primarily focused on studies of regional crustal deformation in the western U.S. and Alaska; but in order to provide additional scientific evidence needed to test regional crustal motion

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models, studies in other geographic areas having both similar and contrasting settings to those in the U.S. are incorporated into the Project. Emphasis is also placed on extensive collaboration with similar international scientific endeavors. The advances made by this Project and the cooperative international programs will help in promoting global scientific understanding of crustal dynamics.

5.2.2 CRUSTAL DYNAMICS PROGRAM ACCOMPLISHMENTS

Most of the Program activity to date has been concerned with regional deformation along the North American-Pacific Plate boundary. Southern California and the Western U.S. are regions of interest because of their appreciable tectonic activity. Measurements begun in 1972 by Moblas stations along the San Andreas Fault are still being made in a follow-on to SAFE. The results indicate the relative velocity of the North American and Pacific plates is essentially constant at a rate of 8 cm \pm 2 cm per year. This rate is considerably higher than the 5.5 cm per year derived for historical plate motion models (Figure 38).

Frequent measurements in California of the length of the baseline between JPL and Goldstone, and between JPL and OVR0, have been made since 1974. In August 1979, remeasurement of these baselines indicated that the position of JPL had shifted about 20 cm to the northwest since the previous measurement in January 1979. During this same interval, several unusual anomalies were observed in Central and Southern California -- changes in the radon content of water wells, gravity changes, changes in creep rate on the San

Table 2
LASER RANGING AND VLBI STATIONS: 1982 STATUS

	Lasers	VLBI
North American Plate	Greenbelt, MD Quincy, CA Plattville, CO Ft. Davis, TX Mazatlan, Mexico (1983)	Westford, MA (NOAA) Greenbank, WV (NSF) Ft. Davis, TX (NOAA) Owens Valley, CA (NSF) Richmond, FL (NOAA 1983) Goldstone, CA Mojave, CA (1983) Algonquin, Canada* Penticton, Canada*
South American Plate	Arequipa, Peru	Sao Paulo, Brazil (1985)
Pacific Plate	Haleakala, HI Monument Peak, CA Society Islands (1982)	Hawaii (1984) Kwajalein (1984)
Eurasian Plate	Kootwijk, The Netherlands* Wetzell, West Germany* Graz, Austria* Mursbach, West Germany* San Fernando, Spain* Olympia, Greece* Caligari, Scotland (1984)* Matera, Italy* Herschen, West Germany (1984)* Zimmern, Switzerland (1984)* Greenwich, England*	Effelsberg, West Germany* Onsala, Sweden* Madrid, Spain* Yebe, Spain* Granada, Spain* Bologna, Italy (1983)* Chilbolton, England* Kashima, Japan (1984)*

* Foreign owned or operated.

Andreas Fault near Parkfield, and changes in the strain observed near the San Andreas Fault by ground surveys. As part of an intensified geophysical study of the area, measurements of the JPL - Goldstone - OVRO baselines were made in late 1979 and early 1980, and further measurements are continuing to be made in this region. Preliminary analysis of the JPL - Goldstone - OVRO measurements made in late 1979 indicate that JPL has moved in different directions about 10 cm between each observing period, and that its position in 1980 was back to what it was in 1978. The validity of these observations is not completely established, and these results must be regarded as tentative, pending review of the VLBI analysis procedures. However, if the results are valid, they are of considerable geophysical importance, since they indicate that large-scale crustal movements may be occurring in Southern California on an unexpectedly short time scale.

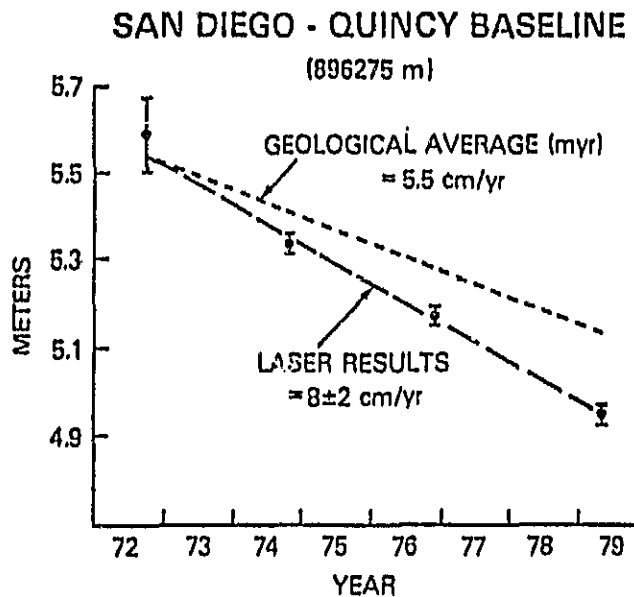


Figure 38 - Motion along the San Andreas Fault

In 1981, initial measurements were made using fifteen sites in California and the Ft. Davis, Texas VLBI station (Figure 39).

Complementary ground geodetic measurements in the western United States have been made and are being compared to space-derived measurements. Precisions of the ground measurements of a few parts in 10^7 have been obtained. Most of the Southern California networks show results consistent with shear strain on the San Andreas Fault. The dilatation in this area showed a long-term decrease until 1978, and then an increase everywhere except on the Garlock network. The rise in dilatation coincided in time with the apparent change of position of JPL with respect to Goldstone and OVRO, which argues against systematic bias in the ground data. In Northern California, the strain at Point Reyes is about 0.6 microstrain/year, the highest observed. The observed shear strain increases from Southern to Northern California.

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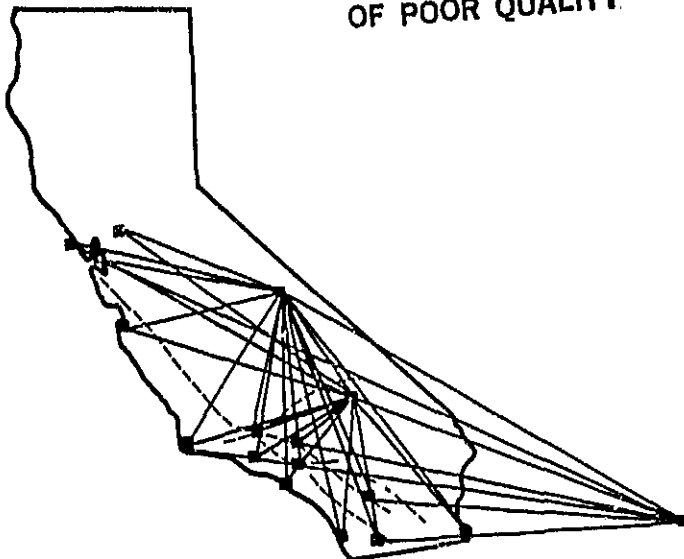


Figure 39 - California regional crustal deformation measurements, 1981

Other supporting ground studies have been made in the western U.S: tilt measurements have been made of Southern California, and investigators are inferring vertical movement from a releveling project recently completed in this region. Strain measurements have been made over the last seven years at Pinon Flat Observatory in California. The 800-m laser strainmeter used is able to resolve normal secular strain at the level of 10^{-7} /year. The results confirm that the crust in this area acts elastically, at least for periods between seismic and tidal frequencies. Secular strain results are consistent with the nearby 15-km geodetic network. Highly accurate ground-based geodetic studies made over the last decade show the following episodic and secular movement occurring in the San Diego - El Centro regions. The relative motion of San Diego with respect to the northeast corner of the region is estimated at 5.0 ± 3.3 cm/year in the direction of $N17^{\circ}W + 5^{\circ}$. Secular slip rates in millimeters/year on different faults in the region are: Imperial, 13 ± 2 ; Brawley, 6 ± 1 ; San Jacinto, 7 ± 2 ; Elsinore 1 ± 1 ; Banning, 10 ± 3 .

Several investigators are combining data types for multi-disciplinary studies of particular regions; for example, seismic, magnetic, and gravity data are being combined with geological and geodetic data for studies in North America and other regions.

New estimates have been made of the direction and rate of motion of the Caribbean Plate, which indicate that the relative motion of North America with respect to the Caribbean is 3.7 ± 0.5 cm/year in the direction $S65^{\circ}W$, using several kinds of evidence. Magnetic anomalies in the mid-Cayman Trough indicate that full spreading rates in this region decreased from 4 to 2 cm/year about four million years ago. Two seismic zones east of the Cayman Trough suggest the presence of a microplate along the northern margin of the Caribbean Plate. The rate of seismic activity along each zone indicates about 2 cm/year movement.

Progress has been made in measuring and analyzing intercontinental baselines using VLBI and SLR techniques (figure 40). Repeated observations of baseline lengths between VLBI observatories in the U.S. and Europe show no changes at the level of 1 cm/year. For example, seventeen VLBI measurements made over two and one-half years between Haystack Observatory in Massachusetts and Onsala Observatory in Sweden show a rms scatter of 3.5 cm; five measurements between Haystack and Effelsberg in West Germany show a 2.2 rms deviation. Predicted movement between North America and Europe is sufficiently slow that observations up to the present are initial-epoch measurements.

The assumption of rigidity at the centimeter level across the breadth of a plate is being tested in North America. Thirty-six measurements since 1972 between Haystack, Massachusetts, and Owens Valley Radio Observatory (OVRO) in California show a baseline length difference of less than 15 cm, or 0.3 ± 0.24 cm/year over this 4,000 km baseline. These transcontinental baseline measurements indicate that if any deformation is occurring, it is at less than 1 cm/year. Long-term measurements are needed to ascertain whether deformation is occurring at less than this rate and to seek reasons for major intraplate earthquakes such as the 1812 earthquake in New Madrid, Missouri.

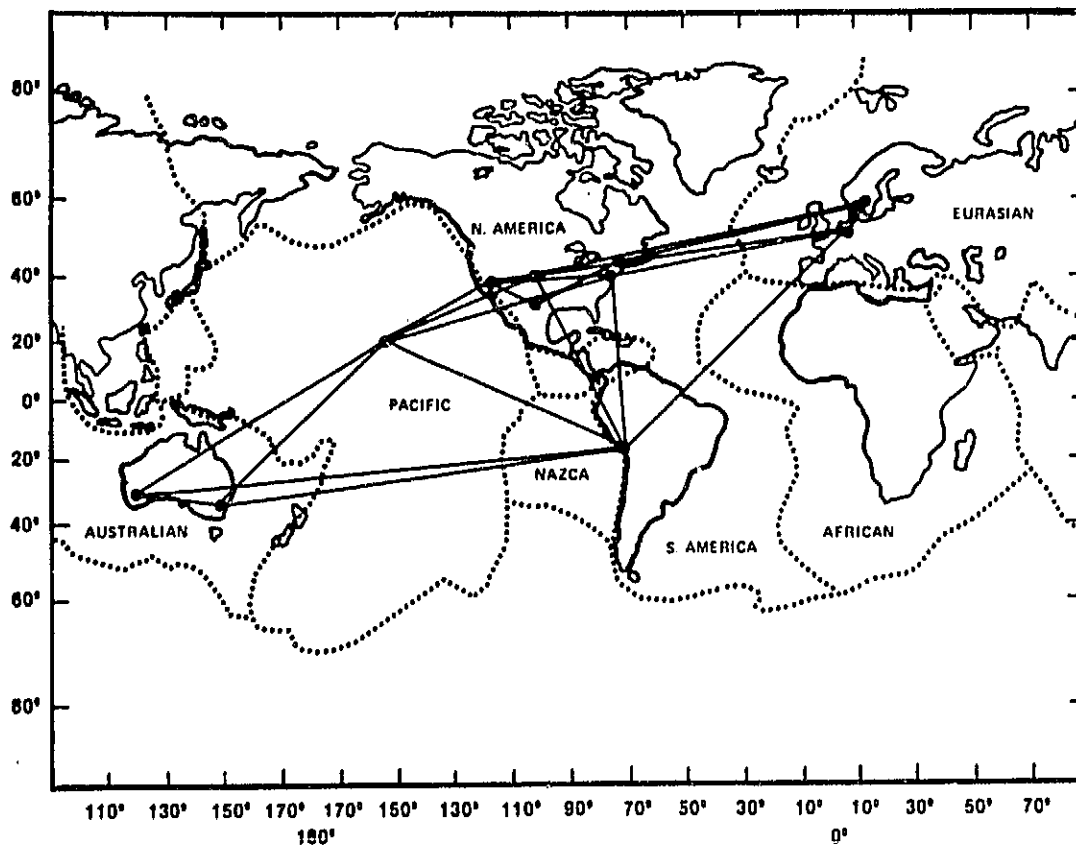


Figure 40 - Tectonic plate motion measurements in 1981

SLR measurements to Lageos have been used to establish 30-day arcs for determining station coordinates. Analysis of the data shows internal consistency of 3-10 cm rms scatter of station coordinates, but a cross-comparison of these results showed an average 20 cm difference. Studies of data analysis techniques are continuing to produce better methods of resolving the data.

Another area of study of crustal motion is the refinement of numerical models and theories for analyzing and predicting crustal movements. The models focus on stress accumulation, deformation, and the causal mechanisms of the stress and their relationship to the rheological properties of the lithosphere and asthenosphere. A multi-layered rheological model (Figure 41) has been formulated to simulate intracrustal damping of geodetic displacements, taking into account the possibility of decoupling within the crust. Results to date indicate that this model obtains good agreement with observations of the strain accumulation cycle on the San Andreas Fault. A different multilayer model of time-dependent deformation following earthquakes of different types (strike-slip, dip-slip, and oblique slip) has also been developed; it entails a viscoelastic model of postseismic crustal movement and a viscoelastic rheology for the lower lithosphere and asthenosphere. The results suggest

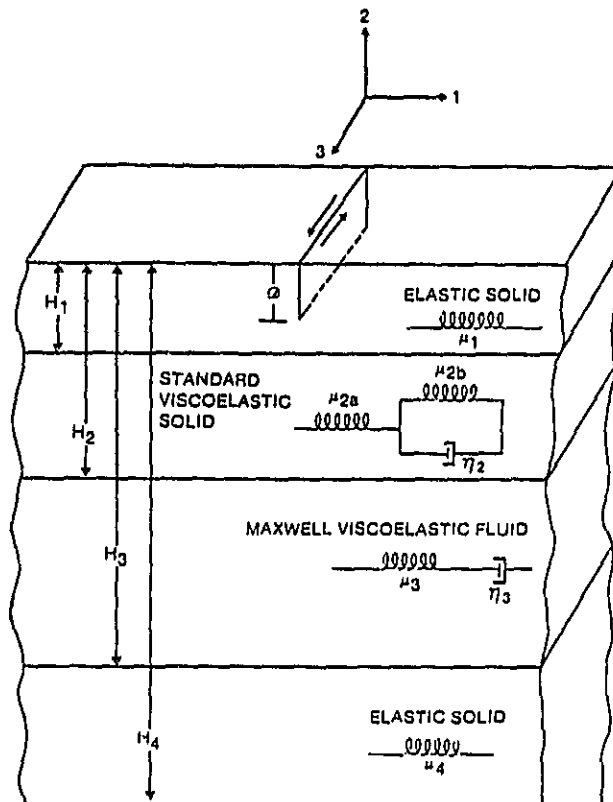


Figure 41 - Multilayer rheological model for post-seismic rebound study

that the most sensitive parameter is the depth to the top of the fastest creeping region; the results are less sensitive to asthenosphere thickness and motion of the lower lithosphere. The results coincide with an independent estimate of the depth of the asthenosphere (30-40 km). The model results for strike-slip earthquakes suggest that diffusion of shear stress away from the fault zone is retarded by a graded viscoelastic profile, compared to a sudden transition between elastic and viscoelastic layers. The compressive stress associated with dip-slip post-seismic movement does not diffuse out of the fault zone. Other theoretical studies of deformation have been modeled for the regions around transform plate boundaries. One model uses a power law creep model for an earthquake mechanism which is sensitive to the power coefficient but provides an estimate of the length scale of ruptures. The surface deformation associated with upward motion of the high strain zone is distributed over distances which are closely correlated to estimates of the lithosphere thickness.

Another study is modeling intraplate deformation and stress. The results show that the mechanical properties of oceanic plates are simple compared to continental plates. The investigators studied areas of intraplate tectonic activity where comparatively well-known sources of stress (for example, loading and topography) may be contributing to the stress field that produces the deformation. Early conceptual results indicate that the total stress field is the sum of these local stresses and an unknown regional stress.

The global intraplate stress field predicted by plate-driving force models has been calculated as a means of testing such models against available observations on midplate stress orientations. The typical magnitude of intraplate stresses is several hundred bars, and local sources of stress of larger magnitude can dominate regional stress. The average changes in stress along faults during earthquakes are typically a small fraction of the total stress. For regional-scale problems, a linear viscoelastic but spatially variable rheology for the lithosphere and asthenosphere has been used to explore the effects of lateral variation in viscosity for both strike-slip and dip-slip earthquakes.

5.2.3 CRUSTAL DYNAMICS PROGRAM PLANS

Most of the Program plans for this decade are structured through the Crustal Dynamics Project. Additionally, several new program initiatives and the deployment of new measuring instruments are being planned.

GPS methods of local surveying, discussed in Section 4.2.3, have been conceived and developed through research in this Program area. Other missions under consideration include a follow-on to Lageos, which when used in conjunction with Lageos could cut measurement time in half.

Another proposed mission (Figure 42a) is the deployment of an Airborne Laser Ranging System (ALRS), in which a laser mounted in an aircraft would be used to range to a grid of cube corner reflectors on the ground. Conceptual studies of the system have been completed and a hardware

schedule developed. This system is expected to provide six-legged range measurements at centimeter-level accuracy.

A similar system (Figure 42b) would involve a laser in space. The Spaceborne Geodynamics Ranging System (SGRS) could range sequentially to several hundred retroreflectors and could map an area the size of the state of California in a few days. These systems could be used to monitor highly seismic areas in the world and to study crustal deformation before and after major earthquakes.

5.2.3.1 Crustal Dynamics Project Plans. Regional deformation measurements in California will be extended to Northern California and to Northern Mexico in 1983. The California sites (Figure 43) will be monitored using fixed and mobile VLBI systems with measurements being obtained at least once per year.

For intercomparison of results some of the sites will also be visited by TLRS-1. TLRS-1 will operate in conjunction with permanent Moblas sites at Quincy and Monument Peak in California and in Mazatlan, Mexico and will also occupy several sites in Mexico (Figure 44).

Beginning in 1984, regional deformation studies in Alaska (Figure 45) will be initiated and will be repeated every year through 1987 to study the crustal strain resulting from the subduction of the Pacific Plate under the North American Plate at the Aleutian Trench.

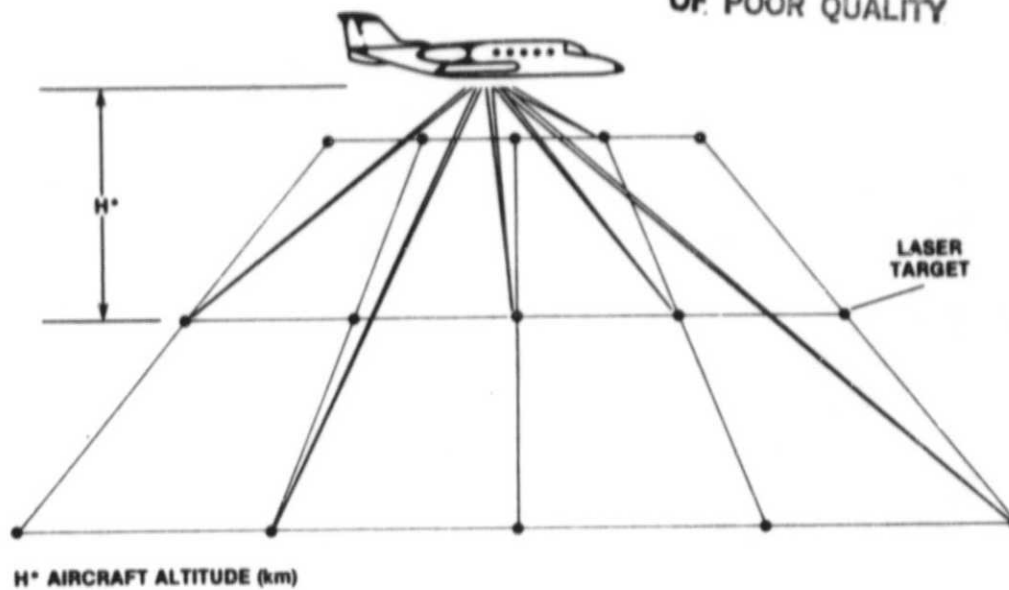
Similar tectonic settings to those in California and Alaska exist in New Zealand (Alpine Fault), in the Eastern Mediterranean (North Anatolian Fault), and in the west coast of South America where the Nazca Plate is subducting under the South American Plate. In order to understand regional deformation in the U.S. and to verify models which are developed from the U.S. measurements, the Project plans to conduct measurements in these other areas in conjunction with scientists from these countries. In South America, TLRS-1 is planned to occupy several sites in Chile and Peru (Figure 46), and possibly Bolivia starting in 1984.

In Europe, Crustal Dynamics Project Principal Investigators have joined with several U.S. investigators in developing a program of study for the Anatolian Fault (Figure 47).

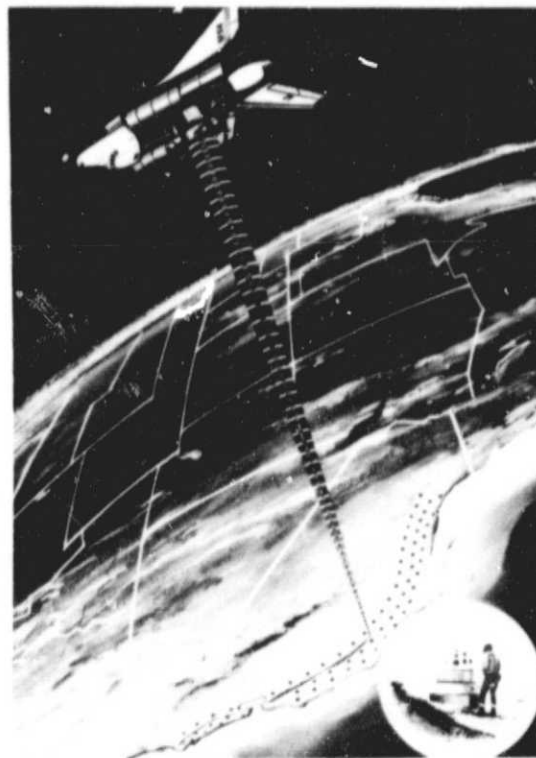
Fixed laser stations in France, the Netherlands, Germany, Italy, Austria (and possibly Greece and Egypt) will be used in conjunction with TLRS-type stations developed by the Germans and Dutch (and possibly Italians). If feasible, the European mobile systems will be joined by a NASA mobile station. Regional deformation measurements in New Zealand (Figure 48) are also planned, and will begin in 1985.

The Caribbean is a complex area of high seismicity. Various types of plate boundary interactions are thought to exist, although information on the magnitudes and directions of the plate motions is sparse. Plans for studies of the Caribbean (Figure 49) have been developed, however these are still evolving and no actual measurements have been scheduled.

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(a) ALRS



(b) SGRS

Figure 42 - Airborne and spaceborne laser ranging systems

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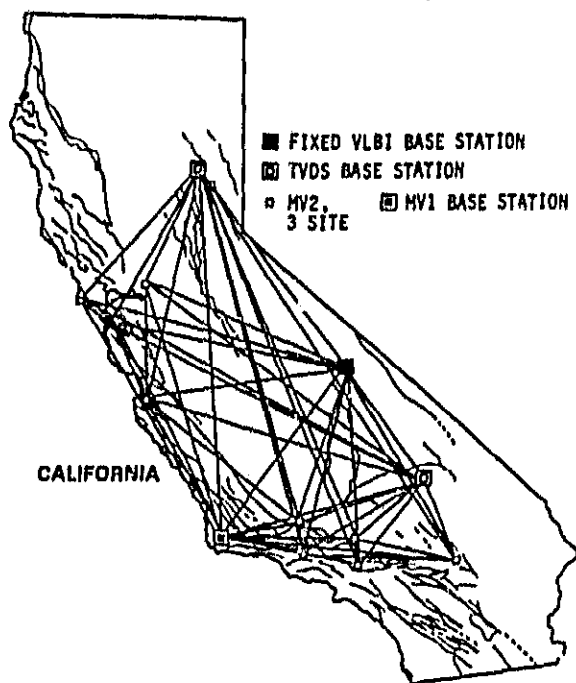


Figure 43 - 1983 VLBI observations

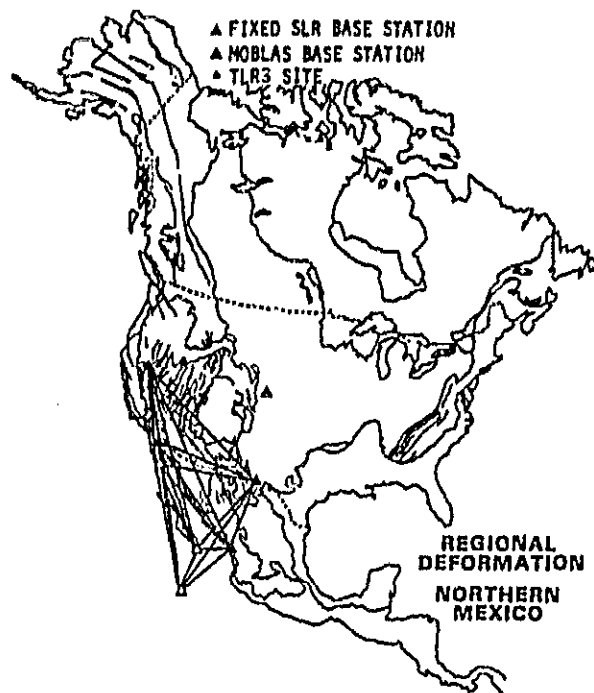


Figure 44 - North American Crustal Dynamics Project sites

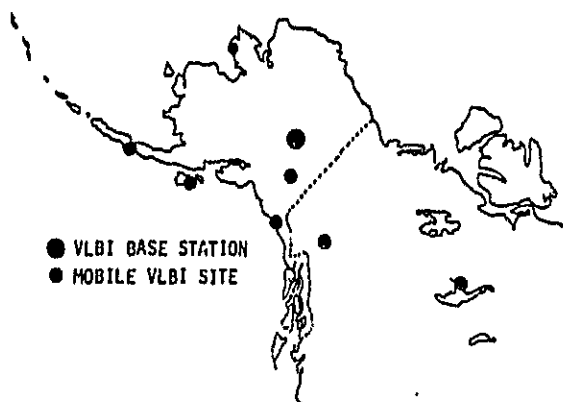


Figure 45 - Alaska regional deformation VLBI stations

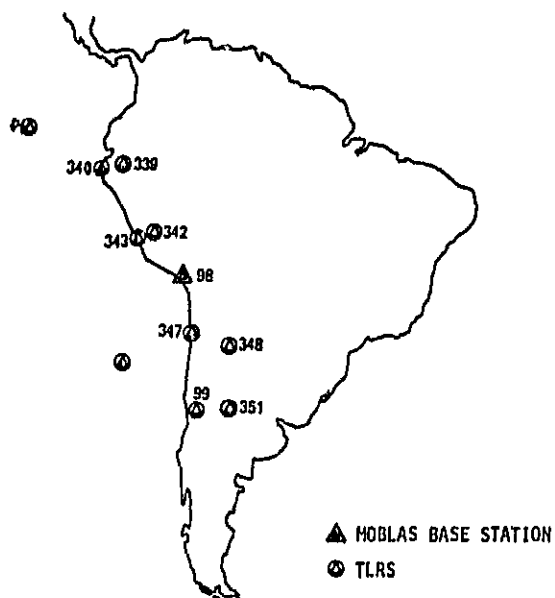


Figure 46 - 1984 TLRs sites

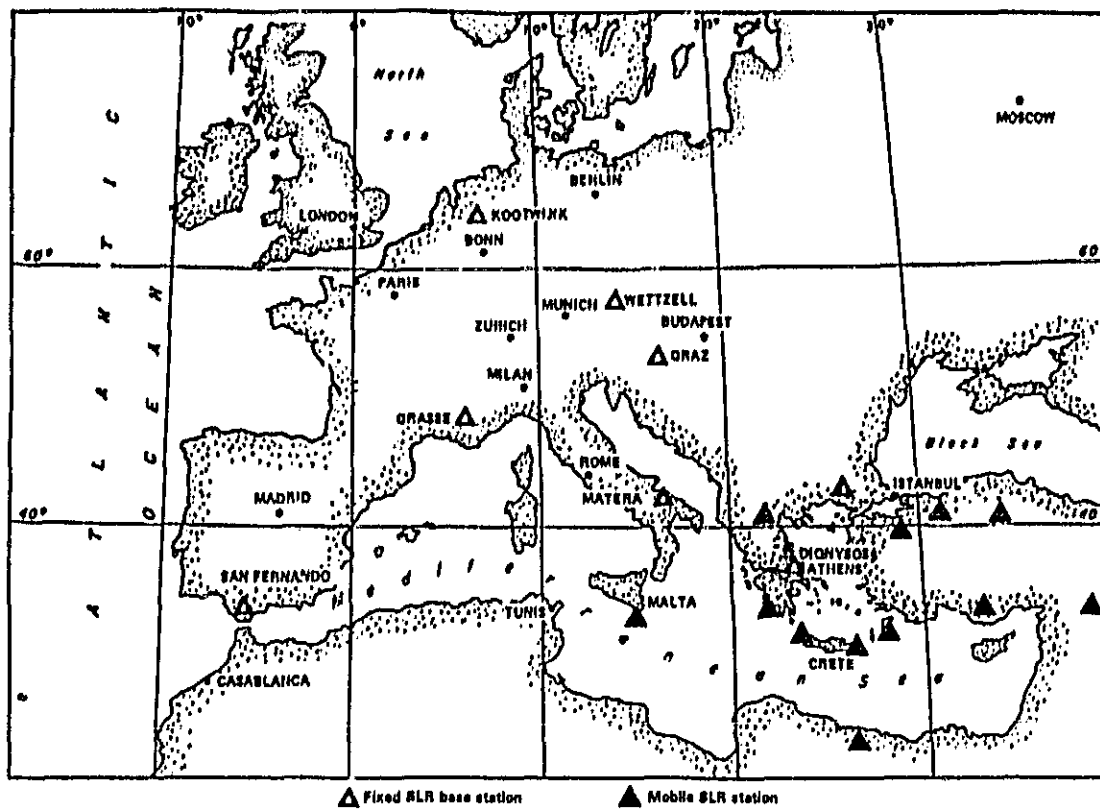


Figure 47 - Proposed SLR sites/stations

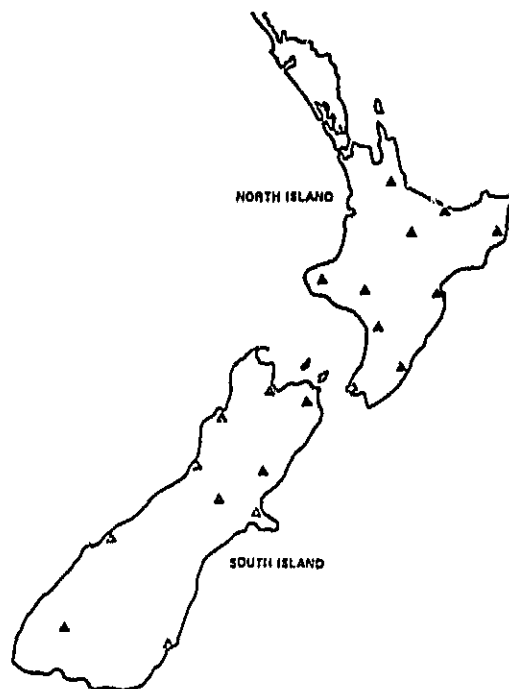


Figure 48 - Proposed sites in New Zealand

Studies of the internal deformation of the North American Plate, including portions of Canada will be continued through 1988 using both fixed and mobile lasers and VLBI systems. Studies of Pacific Plate deformation will rely particularly on laser data acquired from sites in Hawaii and in the Society Islands.

Relative motions of major tectonic plates (North America, South America, Pacific, Nazca, Australia, and Eurasian) will be measured using fixed laser and VLBI systems located on these plates. The initial measurements involving the Nazca Plate will be made in 1983 using TLRS-2. In 1984, the Japanese plan to complete a VLBI station at Kashima, Japan and to begin joint Pacific Plate studies with the U.S.

Existing measuring systems are also being advanced through improvement efforts in hardware and software. VLBI systems are continuing to be upgraded with advanced correlators and processing improvements which should improve the VLBI systematic accuracy of observations from 5 to 1 cm.

Laser ranging systems are being upgraded with new, higher performance lasers, increased mobility and improved daytime tracking capabilities. The intercomparison and data information systems are also seeing some improvement. The Crustal Dynamics Data Base has been implemented and will provide investigators and other scientists with information on station coordinates, baseline lengths, polar motion, length of day, and SLR and VLBI data sets.

The 1980's will be a decade of extensive measuring and analysis of crustal motion. Additional plans call for crustal measurements to enter an operational phase which will see their management by NASA turned over to NOAA. In 1980 NASA initiated space observations at a number of sites in the United States, as part of its Crustal Dynamics Project. Under contract to NASA, NOAA will take over partial responsibility for monitoring of these sites beginning in 1984 as the NOAA National Crustal Motion Network (NCMN, Figure 50). NOAA will use the mobile VLBI systems developed by NASA. The mobile VLBI systems will be related to the Polaris-derived basic reference frame through co-observations with the Polaris stations. NASA will continue observations in the U.S. using laser ranging systems as part of the NCMN. Following completion of the Crustal Dynamics Project, NOAA will continue monitoring of the NCMN.

Another cooperative program of regional deformation measurements is planned for the mid 1980's between NASA and the USGS. Under this plan, NASA will assist USGS in the application of GPS receivers to the monitoring of local crustal motion networks in California.

5.3 GEOPOTENTIAL RESEARCH PROGRAM

The objectives of the Geopotential Research Program are to develop gravity and magnetic field models, to investigate data analysis techniques and software systems, and to support the other elements of the Geodynamics Program, as well as other NASA programs such as the Earth Resources and Oceanic Research Programs. Emphasis is placed on use of satellite data to achieve the maximum resolution for global field measurements.

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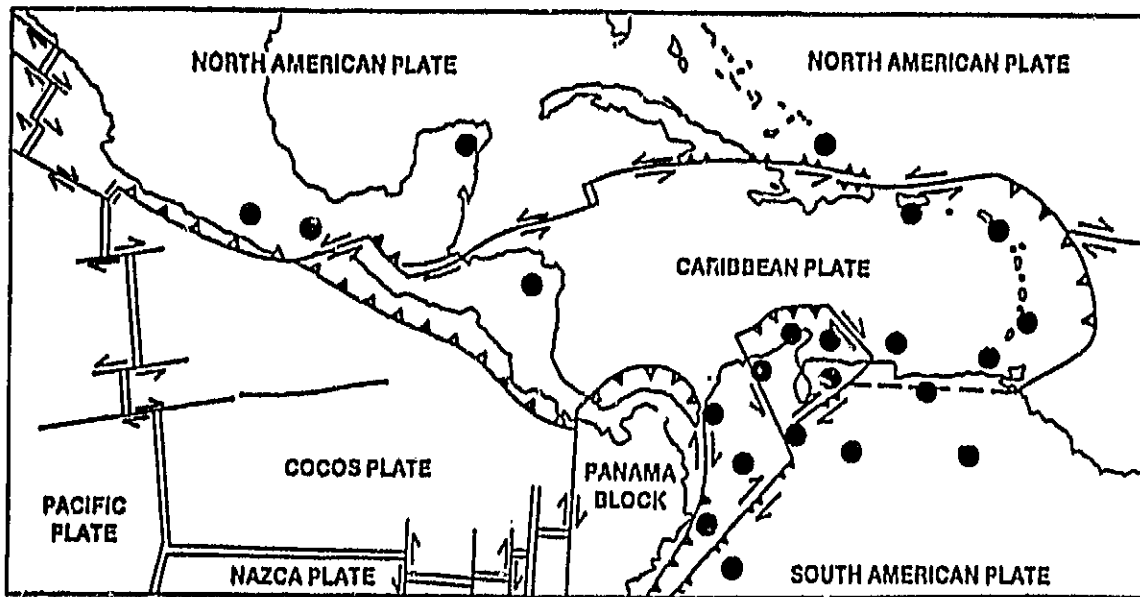


Figure 49 - Tectonic map of the Caribbean region



Figure 50 - National Crustal Motion Network

5.3.1 GEOPOTENTIAL RESEARCH PROGRAM ACCOMPLISHMENTS

Several advances have been made by program investigators in improving gravity field models. Modeling techniques have been developed to improve 5° equal-area average anomalies. A global 1° equal-area average data tape has been developed for use in geophysical studies and geoid computations and has also been used for solutions combining satellite and gravimetric data.

The gravity field of the central Pacific area has been measured using satellite-to-satellite tracking between GEOS 3 at an altitude of about 840 km and ATS 6 at 5.6 Earth radii in a geosynchronous orbit. The measurements are about 70 km apart along track. A low degree and order (less than 12) gravity field was assumed as the reference field in computing the orbits. Using about 50 tracks, these point values were contoured to give a gravity map at an altitude of 840 km. This field shows a dominant wavelength of about 2000 km, often with positive anomalies associated with residual depth anomalies. Significant new anomalies appear near the East Pacific Rise trending in the ridge direction and continuing through North America. An additional group of about 50 new passes has been similarly reduced to produce a map which correlates closely with the newest GEM model, the GEOS geoid, and with the Seasat geoid.

The global set of Seasat radar altimeter data have been used to produce a global $1^\circ \times 1^\circ$ mean sea surface map (Figure 51). Comparisons have been made between these surfaces and geoids computed from GEM gravity models. The rms difference between the GEOS 3 and Seasat mean sea surfaces is 1.1 meters indicating that sub-meter accuracy has been achieved for both surfaces. Adjustments of the origin of the reference ellipsoid for these surfaces indicated differences generally less than 50 cm.

In addition to the geophysical results, some important oceanographic results have been obtained with Goddard Earth Models using satellite altimetry. GEM-9 and GEM-10 have been extended through the addition of worldwide GEOS 3 altimetry to give new solutions, GEM-10B (Figure 52) and GEM-10C, fields that are complete in harmonics to degree 36 and 180, respectively. GEM-9 is a field derived solely from satellite tracking observations, whereas GEM-10 is a combination solution containing surface gravimetry. The accuracy of the ocean geoid for these models has been estimated by using independent altimeter tracks of GEOS 3.

A gravity model (GEM-L1) has been developed to improve the Lageos orbits. This model will be used to compute the baselines derived by satellite laser ranging. Preliminary results indicate that this model can improve Lageos orbit errors from 50 cm to better than 25 cm.

Scientific advances have been made in a variety of other Earth gravity field studies. These included software advances to process and analyze the satellite data and a number of models which incorporate satellite data and other geophysical parameters. Progress has been made in analysis efforts which entail the correlation of satellite-derived data (geoid, image data from Landsat, magnetic anomaly data from Magsat) to existing hypotheses on the tectonic settings of certain regions.

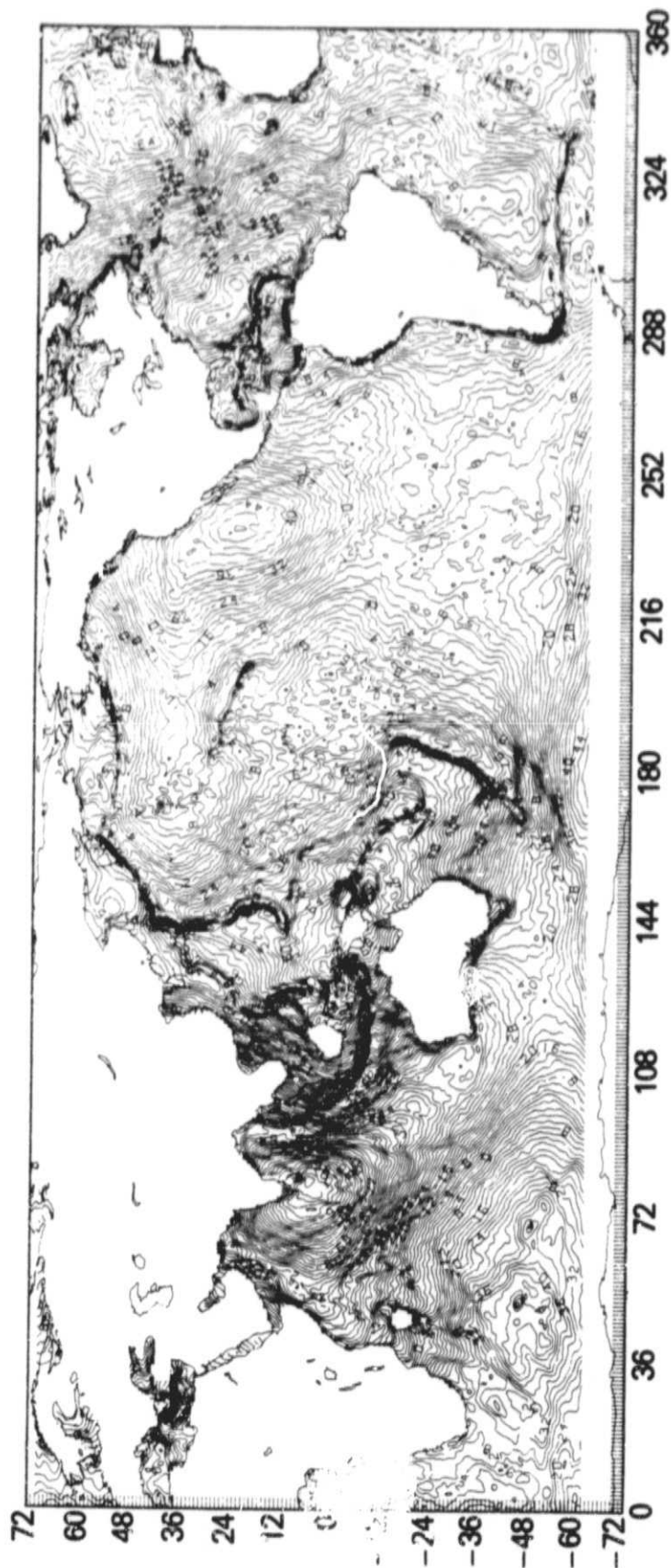
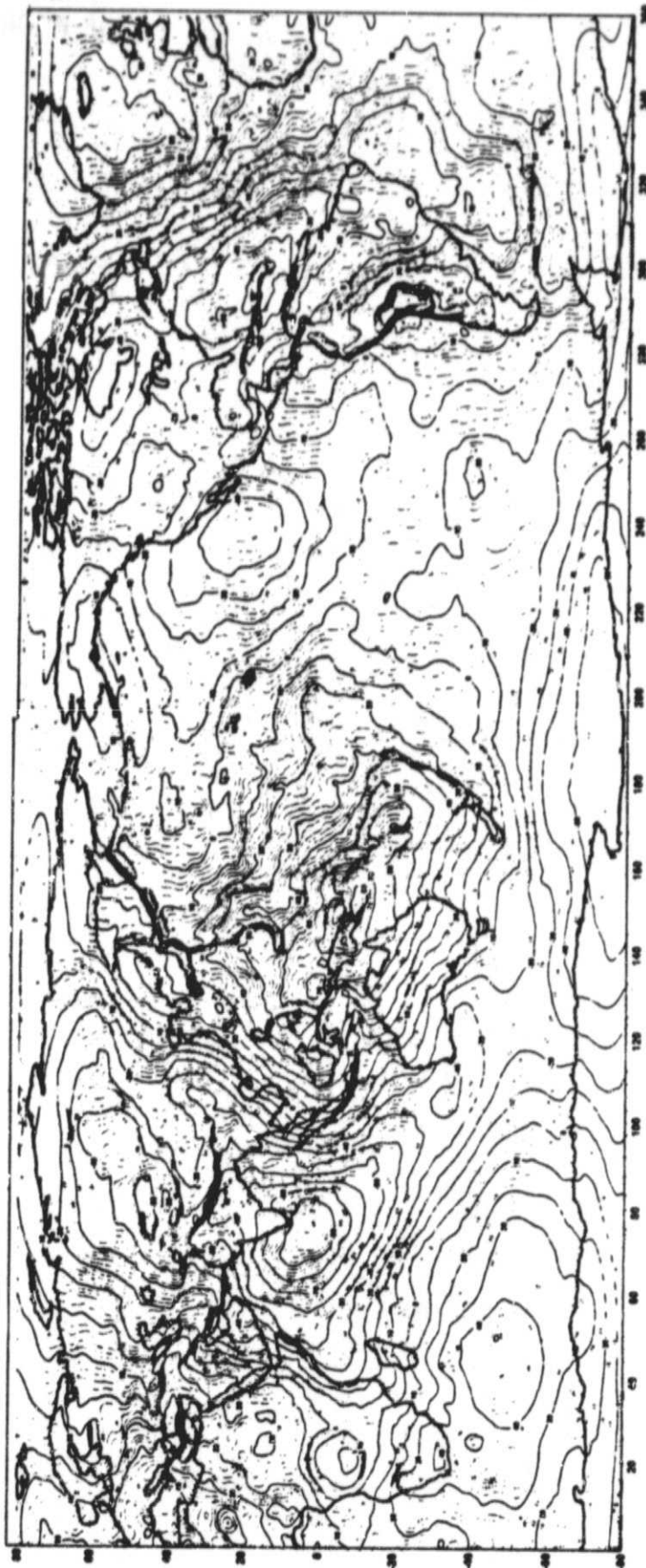


Figure 51 - Mean sea surface topography based upon Seasat altimeter data
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Figure 52 - GEM-10B global detailed gravimetric geoid
(contour interval, 2 meters)

Lunar laser ranging has contributed to investigations of other aspects of gravitation. Certain gravitational relativity theories predict a term in the motion of the Moon that exists neither in Newtonian mechanics nor in Einstein's theory of general relativity. The term, called the Nordtvedt Effect, arises from possible changes in the ratio of gravitational mass to inertial mass due to gravitational self energy. Lunar ranging results show that this term is zero to within quite small limits which effectively eliminates certain theories from serious consideration in relativity theory.

Studies of lunar physical librations have yielded results of importance for lunar science. The fractional moment of inertia ratios have been determined to less than 0.3 percent, along with several higher harmonics of the lunar gravity field. Combining the moment-of-inertia ratios with values of the principal gravity field harmonics from tracking of lunar orbiting spacecraft has made it possible to calculate the normalized principal moment of inertia of the Moon, which is a very important constraint on models of the distribution of mass in the lunar interior, particularly with respect to the question of the existence of a lunar core. Further observations will result in refinement of this determination.

Most of the recent advances in magnetic field studies are due to the highly successful Magsat mission. Magsat reentered the Earth's atmosphere on June 11, 1980 after providing about eight months of data. An initial selection of Magsat data, on particularly magnetically "quiet" days, has been used to derive a series of magnetic field models which have since been adopted as the 1980 International reference field model.

Using the Magsat reference model, investigators were able to process the data so that components from the core (main field) and crust (anomaly field) were separated at the fourteenth order and degree terms. Compared to the earlier POGO data Magsat provides much higher resolution.

Comparisons between crustal anomaly maps produced from both POGO and Magsat models show good correlation with each other and with selected examples of rifts and other known global tectonic features. There is a definite tendency for anomalies to be associated with large features such as shields, platforms, subduction zones, (all with mainly positive anomalies), basins and abyssal plains (with mainly negative anomalies) and to be bounded by "linear" features such as sutures, rifts, folded mountains, and age province boundaries. Magsat crustal maps (Figure 53) have also been constructed to help elucidate the nature and/or origin of certain unknown geological features.

The ability to isolate fields from crustal sources in satellite magnetic field data came as a surprise because of the extremely low amplitude (0-30 nT) of those fields compared to fields originating in the core (30,000 to 60,000 nT) and external to the Earth (0-2,000 nT). The successful isolation of the crustal fields, and subsequent confirmation of their reality, gave impetus to the Magsat Project. In the investigation's preliminary results, attempts are made to isolate not only anomalies in the scalar field but also the anomalies in each component. The apparent success in deriving a vector map in the northern high latitudes is particularly

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Figure 53 - Magsat scalar anomaly map

encouraging in view of the ever present field-aligned and ionospheric currents in this region. Because the southern high latitudes were in sunlight during most of the Magsat lifetime, the ionospheric currents were more severe. Thus the data available for anomaly studies are sparse. In general, anomalies oriented across the satellite track tend to be enhanced while those along track are partially filtered. As a result, the lower latitude maps exhibit east-west trends. Work is continuing in improving data processing techniques for both the scalar and vector measurements.

The contaminating effect of crustal fields on core models becomes a severe problem when extrapolating to the core-mantle boundary where the higher degree/order terms assume a greater importance. Because the deep interior of the Earth is accessible only via a few types of geophysical data, questions of accuracy of core models are important. Theories of the Earth's core have been formulated from the Magsat results. One states that the planetary core is very highly conductive and is surrounded by an insulating mantle.

Although not part of the major mission objectives, Magsat data have also proven useful in the investigation of fields from current systems external to the Earth.

5.3.2 GEOPOTENTIAL RESEARCH PROGRAM PLANS

The results of the Magsat mission and the gravity modeling have led to the concept of a combined mission which would provide improved and correlated measurements of the Earth's gravity and magnetic field. The Geopotential Research Mission builds directly upon the results of earlier spacecraft missions, and at the same time it represents a major step forward in potential field measurements capability. GRM will perform the first globally comprehensive survey of gravitational potential, resulting in significant improvement of existing gravity field models. It will also conduct the first low-altitude global survey of the Earth's vector magnetic field which will permit significantly greater spatial delineation of crustal magnetic anomalies. Finally, the mission will perform the first simultaneous measurements of gravity and magnetic field strength at orbital altitudes, resulting in a coregistered set of potential field data which will permit the development of regional crustal models at a significantly improved level of geological sophistication.

The objective of the GRM is to advance our knowledge of the geopotential with resolution of horizontal features as small as 100 km. This is important to achieving a global assessment of petroleum and mineral resources, to attaining a better understanding of the geophysical processes associated with global tectonics and the occurrence of earthquakes, and to understanding global ocean circulation and the influences of the oceans on weather and climate. The GRM will contribute to our knowledge and understanding of the origin and structure of geological features on the Earth's surface, such as sedimentary basins, continental shields, mountain ranges, island arcs, and ocean trenches (Figure 54). It will allow study of global circulation of the oceans and associated major current systems through the development of an accurate geoid. It will contribute to our understanding of the rheological

properties of the Earth's mantle and the mechanisms that drive lithospheric plates. GRM will provide an improved reference field model for ground-based gravity and magnetic surveys for resource exploration and for precise satellite orbit determination. It will provide additional data to test models formulated from earlier magnetic and gravity measuring missions. The simultaneous measurements of the gravity and magnetic fields, produced by the Earth's structure, will provide information never before available.

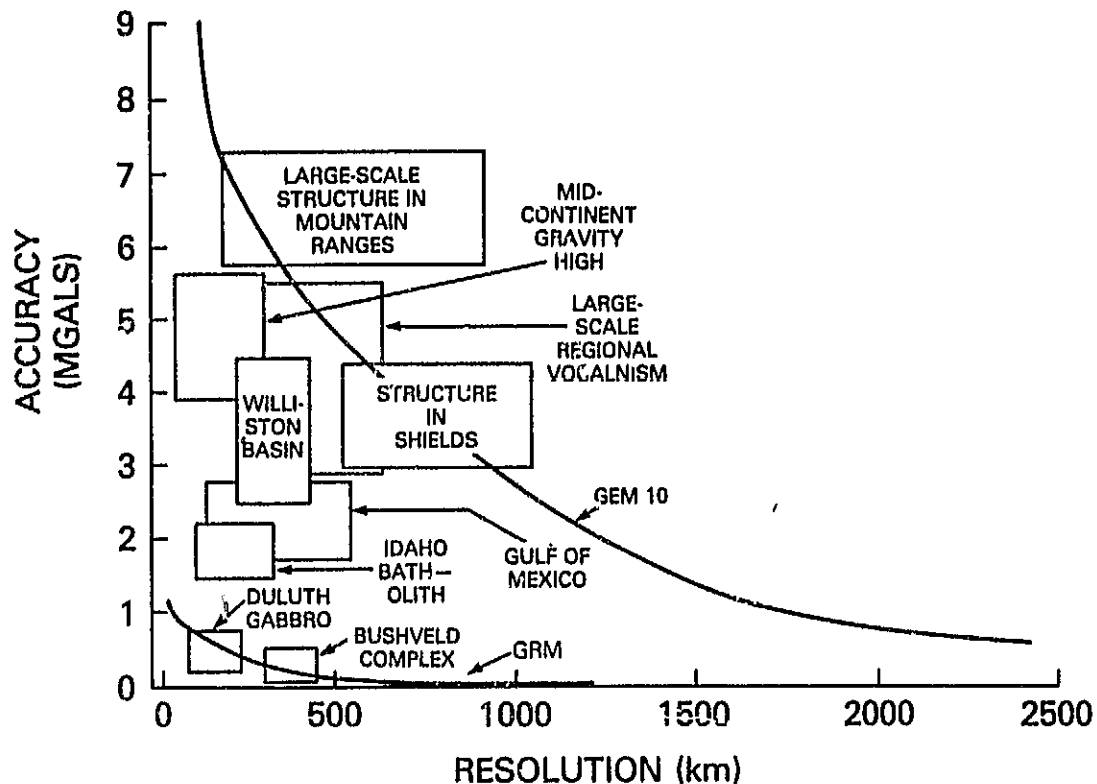


Figure 54 - Global gravity models and economic provinces

The GRM system (Figure 55) is designed to obtain measurements of gravity field strength with an accuracy of ± 2.5 milligal and a spatial (half-wavelength) resolution of 100 km (this corresponds to a gravimetrically defined geoid with an accuracy of ± 10 cm at an equivalent spatial resolution.) Magnetic field measurements will be obtained with an accuracy of approximately 3 nanoteslas in each vector component at a spatial resolution of 100 km. The science requirements for the proposed mission were delineated by the Committee on Geodesy of the National Academy of Sciences, and the mission has been reviewed by a variety of groups both within and outside of NASA. It has received the official endorsement of the National Academy of Sciences, the Satellite Geodesy Applications Board, and leading U.S. scientists involved in potential field research.

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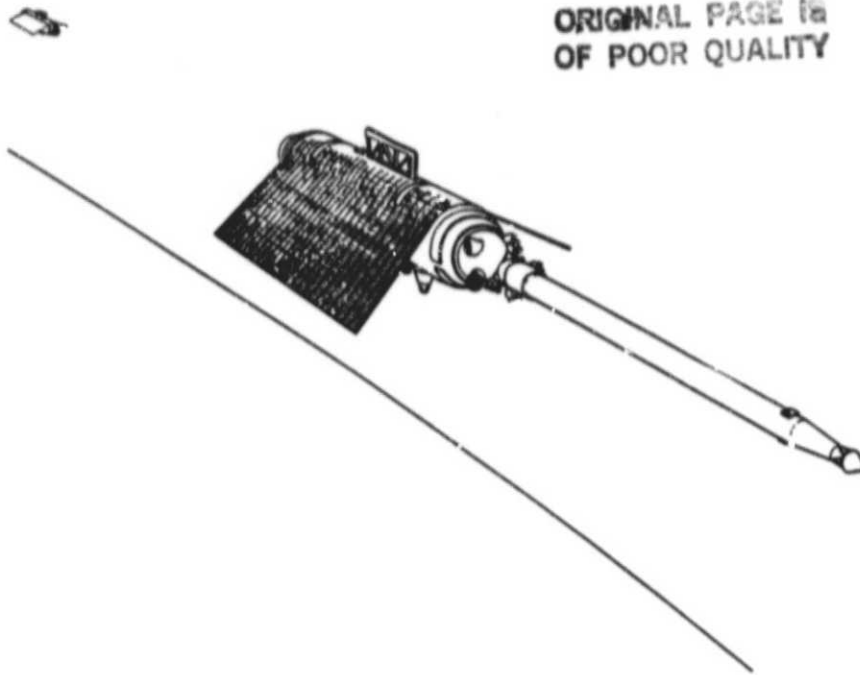


Figure 55 - GRM

GRM consists of two spacecraft which follow one another in orbit at a nominal altitude of 160 km. Gravitational accelerations will be inferred from satellite-to-satellite Doppler tracking data and drag-free satellite technology. Magnetic field measurements will be obtained by magnetometers mounted at the end of a rigid boom on the leading spacecraft. A launch in the 1986 to 1988 period is desired to avoid increased solar sunspot activity in 1988 which could complicate mission operations and the analysis of magnetic field data. Nominal mission lifetime is expected to be seven months.

GLOSSARY

ALRS	Airborne Laser Ranging System
ALSEP	Apollo Lunar Surface Experiment Package
ANNA	Army, Navy, NASA, Air Force
ARIES	Astronomical Radio Interferometric Earth Surveying
ASTP	Apollo-Soyuz Test Program
ATS	Applications Technology Satellite
BIH	Bureau Internationale de l'Heure
CDP	Crustal Dynamics Program, also Crustal Dynamics Project
CEI	Connected Element Interferometry
CIO	Conventional International Origin
COSPAR	Committee on Space Programs and Research (United Nations)
DISCOS	Disturbance Compensation System
DMA	Defense Mapping Agency
DOC	Department of Commerce
DOD	Department of Defense
DSN	Deep Space Network
EDP	Earth Dynamics Program
EODAP	Earth and Ocean Dynamics Applications Program
ERS	European Research Satellite
ESA	European Space Agency
gamma	10^{-5} gauss (also nanotesla)
gauss	Unit of magnetic intensity; equal to 1 dyne per unit pole.
GEM	Goddard Earth Model
geoid	The figure of the Earth considered as a mean sea-level surface.

GEOS	Geodynamics Experimental Ocean Satellite
GM	Product of the gravitational constant and the mass of the Earth.
GPS	Global Positioning System
GRM	Geopotential Research Mission
GRP	Geopotential Research Program
GSFC	Goddard Space Flight Center
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICL	Inter-union Commission on the Lithosphere
ICSU	International Council of Scientific Unions
IGP	International Geodynamics Program
IUGG	International Union of Geodesy and Geophysics
IUGS	International Union of the Geological Sciences
JPL	Jet Propulsion Laboratory
Lageos	Laser Geodynamics Satellite
LASER	Light Amplification by Stimulated Emission of Radiation
LLR	Lunar Laser Ranging
LNO	Laser Network Operations
LORAN	Long Range Navigation
Lure	Lunar Laser Ranging Experiment
Magsat	Magnetic Field Satellite
MERIT	Monitoring of Earth Rotation and Intercomparison of Techniques
mgal	Milligal (10^{-3} cm/sec ² , approximately 10^{-6} g)
MLRS	McDonald Laser Ranging Station
Moblas	Mobile Laser Station
MSFC	Marshall Space Flight Center

MV	Mobile VLBI
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NCMN	National Crustal Motion Network
Nd:YAG	Neodymium:Yttrium/Aluminum/Garnet (type of laser crystal)
NGS	National Geodetic Survey
NGSP	National Geodetic Satellite Program
NLRS	Australian National Mapping Division Laser Ranging Station
NOAA	National Oceanic and Atmospheric Administration
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRL	Naval Research Laboratory
NSSDC	National Space Science Data Center
NSF	National Science Foundation
nT	Nanotesla
OGO	Orbiting Geophysical Observatory
OSSA	Office of Space Science and Applications (NASA)
OSU	Ohio State University
OVRO	Owens Valley Radio Observatory
PAGEOS	Passive GEOS
POGO	Polar Orbiting Geophysical Observatory
Polaris	Polar Motion Analysis by Radio Interferometric Systems
PPME	Pacific Plate Motion Experiment
pps	Pulse Per Second
R&D	Research and Development

rf	Radio Frequency
rms	Root-Mean-Square
RTD	Research and Technique Development
SAFE	San Andreas Fault Experiment
SAO	Smithsonian Astrophysical Observatory
Seasat	Ocean Dynamics Monitoring Satellite
SECOR	Sequential Collocation of Range
SE III	Standard Earth Model III (for gravity field)
SERIES	Satellite Emission Range Inferred Earth Surveying
SGAB	Satellite Geodesy Applications Board
SGRS	Spaceborne Geodynamics Ranging System
SLR	Satellite Laser Ranging
Starlette	French satellite equipped with cube corner retroreflectors
TLRS	Transportable Laser Ranging Station
Topex	Ocean Topography Experiment
TPM	Tectonic Plate Motion
TVDS	Transportable VLBI Data System
UCLA	University of California at Los Angeles
UNESCO	United Nations Educational Scientific and Cultural Organization
USGC	United States Geodynamics Committee
USGS	United States Geological Survey
USNO	United States Naval Observatory
UT	Universal Time
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer

BIBLIOGRAPHY

"Abstracts: Fourth Annual Conference on the NASA Geodynamics Program." NASA Goddard Space Flight Center, Greenbelt, Maryland, 1982.

M.H. Acuna, "The Magsat Precision Vector Magnetometer." Johns Hopkins APL Technical Digest, Volume 1, Number 3, 1980, pp. 210-213.

"Announcement of Opportunity: Crustal Dynamics and Earthquake Research." NASA A.O. No. OSTA 80-2, 1980.

Application of Space Technology to Crustal Dynamics and Earthquake Research. NASA Technical Paper 1464, Geodynamics Program Office, NASA Headquarters, 1979.

Application of Space Technology to Operational Geodynamic and Geodetic Measurement Services. Interagency Coordinating Committee for Geodynamics, July, 1981.

"Applications of a Dedicated Gravitational Satellite Mission." National Academy of Sciences, Washington, D.C., 1979.

E. Bucher, "Motion of the Nodal Line of the Second Russian Earth Satellite (1957B) and Flattening of the Earth," Nature, Vol. 182, 1958, pp. 198-199.

Joseph C. Cain, "Geomagnetic Models from Satellite Surveys." Reviews of Geophysics and Space Physics, Vol. 9, No. 2, May, 1971, pp. 259-273.

Joseph Cain, I.R. Shapiro, J.D. Stolarik, and J.P. Heppner. "Vanguard 3 Magnetic Field Observations." Journal of Geophysical Research, Volume 67, Number 13, pp. 5055.

Charles R. Carrigan, "Multiple Scale Convection in the Earth's Mantle: A Three-Dimensional Study." Science, Vol. 215, 19 February 1982.

S.C. Cohen and T. Peck, "Reports on Crustal Movements and Deformations." NASA Technical Memorandum 83872. Goddard Space Flight Center, Greenbelt, Maryland, 1981.

A.H. Cook, Physics of the Earth and Planets, John Wiley and Sons, New York, 1973.

Robert and Barbara Decker, Intro., Volcanoes and the Earth's Interior, Readings From Scientific American, W.H. Freeman, San Francisco, 1982.

Dewey, J.F., "Plate Tectonics." Scientific American, (Offprint, N. 900), W.H. Freeman, San Francisco, May 1972.

Dictionary of Geological Terms, Anchor Press/Doubleday, Garden City, New York, 1974.

"Dynamics and Evolution of the Lithosphere." Inter-Union Commission on the Lithosphere, 1981.

Earth and Ocean Physics Applications Program, 2 Volumes. NASA, Washington, D.C., 1972.

"Execution Phase Project Plan for Crustal Dynamics." NASA Goddard Space Flight Center, 1980.

W.H. Farthing, "The Magsat Scalar Magnetometer." Johns Hopkins APL Technical Digest, Volume 1, Number 3, 1980, pp. 205-209.

Edward A. Flinn, "Discussion with Investigators Involved in Measurements in the Eastern Mediterranean." NASA Internal Memorandum, September 11, 1981.

Edward A. Flinn, "Discussion with Investigators Involved in Measurements in the Caribbean." NASA Internal Memorandum, September 11, 1981.

Edward A. Flinn, "Report on Geodynamics Conference." (NASA Headquarters Internal Memo.), 1982.

Edward A. Flinn, "4th NASA Geodynamics Conference" EOS Transactions, Vol. 63, No. 19, May 11, 1982.

Geodesy: Trends and Prospects. Committee on Geodesy, Assembly of Mathematical and Physical Sciences, National Research Council, National Academy of Sciences, Washington, D.C. 1978.

Geodetic Monitoring of Tectonic Deformation - Toward A Strategy. Panel on Crustal Movements, Measurements, Assembly of Mathematical and Physical Sciences, Nat'l. Research Council, Nat'l. Academy of Sciences, N.A.S. Press, Washington, D.C., 1981.

"Geodynamics Experimental Ocean Satellite Project." Wallops Flight Center-NASA.

"Geodynamics in the 1980's." National Research Council, National Academy of Sciences, Washington, D.C., 1980.

"Geodynamics Program." NASA Headquarters Internal Presentation, March 24, 1982.

GEOS 3 Project. Reprinted from Journal of Geophysical Research, Volume 84, Number B8, July 30, 1979.

M. Grant Gross, Oceanography: A View of the Earth, Prentice-Hall, Inc., New Jersey, 1977.

Bruce Hobs, Winthrop Means, and Paul Williams, An Outline of Structural Geology. John Wiley & Sons, New York, 1976.

Impact of Technology on Geophysics. National Academy of Sciences, Washington, D.C., 1979.

"Interagency Coordination Plan for Development of the Application of the New Global Positioning System (GPS) for Geodetic Surveying." NGS, DOD, USGS, July, 1980.

Imre G. Izsak, "Tesseral Harmonics of the Geopotential and Corrections to Station Coordinates" Journal of Geophysical Research, Vol. 69, No. 12, June 15, 1964, pp. 2621-2630.

Glyn Jones, editor, International Conference on Mathematical Problems of the Thermal and Dynamical State of the Earth Conference Report: Texas A&M University, 1980.

W.D. Kahn, F.O. von Bun, D.E. Smith, T.S. Englar, E.P. Gibbs. "Performance Analysis of the Spaceborne Laser Ranging System." Bulletin Geodesy, Vol. 54, 1980, pp. 165-180.

W.M. Kaula, "Current Knowledge of the Earth's Gravitational Field from Optical Observations." Journal of Geophysical Research, Vol. 68, 1963, pp. 473-484 and 5183-5190.

Desmond King-Hele, "The Shape of the Earth," Science, Vol. 192, No. 4246, 25 June 1976.

Charles Kittel, Introduction to Solid State Physics, 5th Edition, John Wiley & Sons, Inc. New York, 1976.

"LAGEOS Plate Tectonics Satellite." Bendix Aerospace Systems Division, (brochure).

R.A. Langel, editor. "The Magnetic Earth as Seen from Magsat, Initial Results." Geophysical Research Letters, Vol. 9, No. 4, April 1982, pp. 239-242.

R.A. Langel, "Magsat Scientific Investigations." John Hopkins APL Technical Digest, Volume 1, Number 3, pp. 214-227, 1980.

R.A. Langel, R.H. Estes, G.D. Mead, E.B. Fabiano, E.R. Lancaster, "Initial Geomagnetic Field Model from Magsat Vector Data" Geophysical Research Letters, Vol. 17, No. 10, October 1980, pp. 793-796.

R.A. Langel, R.H. Estes and G.D. Mead, "Some New Methods in Geomagnetic Field Modeling applied to the 1960-1980 Epoch," NASA Technical Memorandum 83868, GSFC, December 1981.

Robert Langel, Gilbert Ousley, John Berbert, James Murphy, Mark Settle. "The Magsat Mission." Geophysical Research Letters, Vol. 9, No. 4, April 1982, pp. 243-245.

"Laser Ranging System Development for Crustal Dynamics Applications." NASA Office of Space and Terrestrial Applications, 1980.

Henry Lepp, Dynamic Earth, McGraw-Hill Book Company, New York, 1973.

Francis J. Lerch, Roy E. Laubscher, Steven M. Klosko, David E. Smith, Ronald Kolenkiewicz, Barbara H. Putney, James C. Marsh and Joseph E. Brown. "Determination of the Geocentric Gravitational Constant from Laser Ranging on Near-Earth Satellites." Geophysical Research Letters, Vol. 5, No. 12, December 1978.

Francis Lerch, Barbara Putney, Carl Wagner, and Steven Klosko. "Goddard Earth Models for Oceanographic Applications (GEM 10B and 10C)." Marine Geodesy, Volume 5, Number 2, 1981, pp. 145-187.

Henry Linder, "Data Management Plan for Crustal Dynamics Project." NASA Goddard Space Flight Center, Greenbelt, Maryland, 1981.

"Meetings. Geomagnetic Workshop." EOS, Vol. 63, No. 35, August 31, 1982, pp. 645-649.

J.B. Minster and T.H. Jordan, "Present Day Plate Motion." Journal of Geophysical Research, Vol 83, November 1978, pp 5331-5354.

F.F. Mobley, "Magsat Performance Highlights." John Hopkins APL Technical Digest, Volume 1, Number 3, 1980, pp. 175-178.

"NASA Geodynamics Program: Annual Report for 1979." NASA Technical Memorandum 81978. Geodynamics Program Office, 1980.

"NASA Geodynamics Program: Annual Report for 1980." NASA Technical Memorandum 84010. Geodynamics Program Office, 1981.

"NASA Geodynamics Program: Annual Report for 1981." NASA Technical Memorandum 85126. Geodynamics Program Office, 1982.

NASA Very Long Baseline Radio Interferometry Programs, Status and Plans, Offices of Space and Terrestrial Applications and Space Tracking and Data Systems, NASA Headquarters, December 1979.

National Geodetic Satellite Program, 2 Volumes. NASA SP-365, 1977.

C.E. Noll, "The Development of Selected Data Base Applications for the Crustal Dynamics Data Information System." NASA Technical Memorandum 83886, Goddard Space Flight Center, Greenbelt, Maryland, 1981.

J.A. O'Keefe, Ann Eckels, and R.K. Squires, "Vanguard Measurements Give Pear-Shaped Component of Earth's Figure," Science, Vol. 129, No. 3348, February 27, 1959, p. 565.

Jack Oliver, "Probing the Structure of the Deep Continental Crust." Science Vol. 216, 14 May 1982, pp. 689-692.

G.W. Ousley, "Overview of the Magsat Program." Johns Hopkins APL Technical Digest, Volume 1, Number 3, 1980, pp. 171-174.

T.A. Potemra, "Studies of Auroral Field-Aligned Currents with Magsat." Johns Hopkins APL Technical Digest, Volume 1, Number 3, 1980, pp. 228-232.

T.A. Potemra, F.F. Mobley, and L.D. Eckard, "The Geomagnetic Field and Its Measurement: Introduction and Magnetic Field Satellite Glossary." Johns Hopkins APL Technical Digest, Volume 1, Number 3, 1980, pp. 162-170.

"Preliminary Execution Phase Project Plan for Gravity and Magnetic Satellite." Goddard Space Flight Center, 1981.

Frank Press and Raymond Siever, Earth. W.H. Freeman and Company, San Francisco, 1974.

Radio Interferometry Techniques for Geodesy. NASA Conference Publication 2115, 1979.

Richard Rapp, "GEOS 3 Data Processing for the Recovery of Geoid Undulations and Gravity Anomalies." Journal of Geophysical Research, Volume 84, Number B8, 1979, pp. 3784-3792.

"Remote Sensing Advanced Planning." OAO Corporation, Greenbelt, Maryland, 1981.

P. Rona, Plate Tectonics, Energy and Mineral Resources, EOS, Trans. American Geophysical Union, 58, 630, 1977.

Significant Achievements in Satellite Geodesy, 1958 - 1964, NASA SP-94, Washington, D.C.: U.S. Government Printing Office, 1968.

Eric Silverberg and Deborah Byrd. "A Mobile Telescope for Measuring Continental Drift." Sky and Telescope, May 1981, pp. 405-408.

David E. Smith, "Dynamic Satellite Geodesy." Reviews of Geophysics and Space Physics, Vol. 17, No. 6, September 1979.

D.E. Smith, F.J. Lerch, J.G. Marsh, C.A. Wagner, R. Kolenkiewicz, and M.A. Khan, "Contributions to the National Geodetic Satellite Program by Goddard Space Flight Center." Journal of Geophysical Research, Vol. 81, No. 5, February 10, 1976.

Frank D. Stacey, Physics of the Earth, John Wiley & Sons, Inc., New York, 1969.

H. Ray Stanley, "The GEOS 3 Project." Journal of Geophysical Research, Volume 84, Number B8, 1979, pp. 3779-3783.

D.J. Stevenson, "Models of the Earth's Core." Science, Volume 214, Number 4521, 1981, pp. 611-616.

Arthur N. Strahler, The Earth Sciences, Harper & Row Publishers, New York, 1971.

B.D. Tapley et. al., "Seasat Altimeter Calibration: Initial Results." Science, Volume 204, 29 June 1979, pp. 1410-1412.

D.W. Trask and C.J. Vegos, "Crustal Dynamics Project Review: Mobile VLBI Measurement Program." NASA Internal Report, 1982.

F.O. von Bun, W.D. Kahn, W.T. Wells, and T.D. Conrad, "Determination of $5^{\circ} \times 5^{\circ}$ Gravity Anomalies Using Satellite-to-satellite Tracking Between ATS-6 and Apollo." Geophysical Journal of the Royal Astronomical Society, Vol. 61, 1980, pp. 645-658.

W.J. Webster, Jr., P.D. Lowman, Jr., and R.J. Allenby, "On the Geodetic Stability of the Goddard Optical Research Facility." NASA Technical Memorandum 82175. Goddard Space Flight Center, Greenbelt, Maryland, 1981.

J. Tuzo Wilson (compiler), Continents Adrift - Readings From Scientific American, W.H. Freeman, San Francisco, 1970.

Carl Wunsch, R.J. Anderle, H. Bryden, B. Douglas, D. Halpern, W. Haxby, J. Marsh, R. Rapp, J. Reid, F. Schott, R. Stewart, B. Tapley, D. Thompson, E. Walsh, and K. Wyrski, Satellite Altimetric Measurements of the Ocean: Report of the TOPEX Science Working Group, Pasadena California: NASA/JPL, California Institute of Technology, March 1, 1981.

Alfred Zmuda, editor, "World Magnetic Survey 1957-1969." IAGA Bulletin No. 28, International Union of Geodesy and Geophysics Publication Office, Paris, 1971.

APPENDIX A. EARTH DYNAMICS INVESTIGATIONS

E-1 Lageos Study of Polar motion, Plate Rigidity and Plate Motions.

W. Jason Morgan, Princeton University

Study the role of earthquakes and meteorology in excitation of the Chandler wobble in Polar motion along with the interpretation and modeling of plate rigidity and plate motion.

E-2 Determination of Polar Motion and Earth Rotation from Lageos Data.

David E. Smith, Goddard Space Flight Center

Study earth rotation to determine the form and excitation of the annual and Chandler motions of the pole of rotation to define and understand the secular motion of the mean pole, and to seek the causes of short period variations in the Earth's rotation rate.

E-3 Validation, Intercomparison, and Use of Laser Ranging and Radio Interferometric Data for the Determination of Geophysical Parameters.

Irwin I. Shapiro, Smithsonian Astrophysical Observatory

Validate techniques of lunar laser ranging, and very-long-baseline interferometry for determination of geophysical quantities at the accuracy level of 10 cm or less. Provide a body of reliable data on Earth rotation, polar motion, vector baselines, and solid-earth tides for use in geophysical studies relating mainly to plate tectonics.

E-4 Comparative Studies of Polar Motion by Laser and Doppler Techniques.

F. Nouel, Groupe de Recherches de Geodesie Spatiale, France

Colocate doppler receivers with Lageos laser ranging stations and intercompare position measurement determined by the two methods.

E-5 Determination of Polar Motion and Earth Rotation from Lageos Data.

Deiter Lelgemann, Satellitengeodasie der Technischen Universitat, West Germany

Validate the accuracy level of the laser tracking station at Wettzell, by deriving such geophysical observations as polar motion, and Earth rotation from Lageos observations.

- E-6 Study of the Use of Laser Ranging and Very Long Baseline Interferometry Data in the Routine Rapid Determination of Earth Orientation Parameters

Dennis D. McCarthy, U.S. Naval Observatory

Determine the standard UT1-UTC time scale and polar variations by use of laser ranging and VLBI techniques in conjunction with more classical methods.

- E-7 Contribution of G.R.G.S. to a Crustal Dynamics Program Based on Satellite Laser Ranging

F. Barlier, Centre d'Etudes et Recherches Geodynamiques et Astronomique, France

Establish a worldwide reference system; analyze constraints imposed by a long-lived operational system on the determination of Earth rotation parameters using SLR techniques; and determine total parameters from combined observations of Starlette and Lageos.

- E-8 Measurement of Contemporary Tectonic Plate Motions by Very Long Baseline Interferometry

Thomas A. Clark, NASA, Goddard Space Flight Center

Study north-south VLBI baselines to determine both components of polar motion, uncorrupted by UT1 variations.

- E-9 Earth Rotation and Planetary Motion Studies with Lunar Laser Ranging and Lageos Data

Peter J. Shelus, McDonald Observatory, The University of Texas at Austin

Derive Earth rotation and polar motion parameters, station coordinates, and baselines and study methods for determining judicial points of laser ranging telescopes to coordinate reference frame ties.

- E-10 Study of the Earth-Moon System by Lunar Laser Data Analysis

Odile Calame, Centre d'Etudes et Recherches Geodynamiques et Astronomique, France

Study polar motion and Earth rotation using lunar laser ranging data.

E-11 Lunar Laser Ranging Data Analysis and Modeling

James G. Williams, Jean O. Dickey, Charles F. Yoder, Jet Propulsion Laboratory

Analyze lunar laser ranging data to provide improved estimates of GM_{EARTH}, geocentric station location, tidal components and to support Earth rotation studies through improved modeling, analysis and generation of residuals for long data spans. The ultimate goal is the modeling of the Earth-Moon system at the 3-5 cm level.

E-12 Analysis of Lunar Laser Ranging Data for Earth Dynamics Applications

Irwin I. Shapiro, Smithsonian Astrophysical Observatory

Analyze lunar laser ranging observations to provide UT, polar motion, nutation, rotation rate, GM, and tides for use in geophysical studies. Compare LLR estimates of Universal Time and polar motion with those obtained by satellite Doppler, SLR, VLBI, and classical optical techniques

E-13 Study of the Effect of Inner Core, Fluid Core, and Oceans on Earth Rotation, Nutation and Polar Motion

C.F. Yoder, Jet Propulsion Laboratory

Examine the complex interaction of pressure, gravity, and the Earth's magnetic field in the Earth's core and how it may influence the dynamical motion of the Earth.

E-14 Three-Dimensional Modeling of Post-Seismic Polar Motion

Martin A. Slade and Arthur Raefsky, Jet Propulsion Laboratory

Use numerical modeling of post-seismic motions surrounding a fault in a three-dimensional spherical Earth in order to examine the importance of such motions in exciting the Chandler Wobble. Examine the role of the rheology and viscosity structure of the upper mantle, both from the excitation viewpoint and from the perspective of understanding what geodetic measurements after a large earthquake would elucidate concerning the lithosphere and asthenosphere.

E-15 Geophysical Interpretation of Spatial Geodetic Data

B. Lago, Centre Nationale d'Etudes Spatiale, France

Use SLR, LLR, VLBI and Doppler data along with altimeter parameters to determine the position of the pole and the geophysical effects of seismic and atmospheric sources of excitation to determine tidal parameters (coefficients and phase lag of ocean tides and phase lag of Earth tide) and study dissipation of the Earth-Moon system, and to produce an improved model of global gravitation.

E-16 Effects of the Ocean on Polar Motion

Steven R. Dickman, State University of New York - Binghamton

Investigate the possibility of a free wobble of the oceans, the conditions under which it can exist, its probable nature, and its effects on Earth's rotation.

E-17 Studies of Polar Motion, Earth Rotation and Plate Motions

W. Jason Morgan, Princeton University

This investigation consists of two parts; first, a study of polar motion and variations in Earth rotation and their correlation with other geophysical phenomena, such as atmospheric motions and earthquakes, and second, a study of plate rigidity and plate motions using baselines computed between stations on the same plate.

E-18 Atmospheric Excitation of Changes in Earth Rotation and Polar Motion

Richard D. Rosen, Atmospheric and Environmental Research, Inc.

Develop a time-series of global atmospheric motion and mass fields to compare with changes in length of day and polar motion.

E-19 Analysis of Variable Earth Rotation for Geophysical Sources

Charles F. Yoder, Jet Propulsion Laboratory

Study variations in Earth rotation by removing meteorological variations and examining geophysical factors in the residue.

E-20 Earth Dynamics Analyses

William M. Kaula, University of California

Explain the longer wavelength (>1000 km) variations of the Earth's gravity field as the consequence of mantle convection and its interaction with the lithosphere and crust.

E-21 The Thermal Structure of Convection with Large Viscosity Variations

S.F. Daly, Jet Propulsion Laboratory

Use numerical techniques to study the properties of convection in a plane layer with temperature and depth dependent viscosities over a large parameter range.

E-22 Seismic Wave Velocity Structure in the Downgoing Slab and the Olivine-Spinel Phase Change

Peter Molnar and S. Roecker, Massachusetts Institute of Technology

Study the seismic wave velocity structure in the downgoing slab in a subduction zone.

E-23 A Study of the Effects of Moving: Continental Wakes

E.M. Parmentier, Brown University

Study geoid lows and anomalously shallow sea floors that occur behind drifting continents such as south of India, southwest of Australia, and east of North and South America.

E-24 Dynamic Processes of Convergent Plate Margins

David C. McAdoo, NASA, Goddard Space Flight Center

Develop a model of induced corner flow in the mantle to describe this regional compensation. Compare model results in the form of geoid slope profiles, with profiles of geoid slopes derived from Seasat data and global gravity models.

E-25 Altimetry Data and the Deep Structure of Subduction Zones

M. Caputo, Texas A&M University

Use GEOS-3 altimetry profiles over subduction zones and the derived residual geoid anomalies to construct numerical models of flow and temperature in subduction zones to understand the deep structure of these regions and to address the question of the depth to which the return flow extends.

E-26 The Relationship Between Gravity and Bathymetry in the Pacific Ocean

A.B. Watts, Lamont-Doherty Geological Observatory

Analyze long wavelength gravity and topography anomalies in the Pacific ocean and the plan form and scale of mantle convection using gravity anomaly, bathymetry, magnetic anomaly, seismic reflection and geoid data over the Pacific ocean.

E-27 Electromagnetic Deep-Probing (100-1000 km) of the Earth's Interior from Artificial Satellites; Constraints on the Regional Emplacement of Crustal Resources.

John F. Hermance, Brown University

Evaluate the applicability of electromagnetic deep-sounding experiments using natural sources in the magnetosphere.

E-28 Global Study of the Time Evolution of the Lithosphere Using GEOS-3 and Seasat Altimeters

Micheline C. Roufosse, Smithsonian Astrophysical Observatory

Use radar altimeter data from GEOS-3 and Seasat to investigate the mechanical properties of the lithosphere and the influence of plate velocity on these properties.

E-29 Thermal Isostasy in the World's Oceans

Gerald Schubert, University of California

Determine the thermomechanical structure of the oceanic upper mantle by using the information contained in measurements of geoid height, seafloor depth, and heat flow.

E-30 Solid Earth Dynamics Using Lageos Range Observations.

Byron D. Tapley, University of Texas, Austin

Apply laser ranging data to the determination of polar motion, UT1, and length of day, and to the interpretation of these results in terms of appropriate geophysical models.

E-31 Investigation of Lageos Laser Data at GRGS/Grasse.

F. Barlier, Groupe de Recherches de Geodesie Spatiale, France

Study the effects of gravitational and non-gravitational forces on the orbital parameters of Lageos, and determine the extent to which knowledge of non-gravitational forces affects determination of the gravitational forces.

E-32 Analyze Satellite Tracking Laser Data in Order to Study Satellite Ephemerides, Solid-Earth and Ocean Tides and Laser System Performance.

E.M. Gaposchkin, M.I.T. Lincoln Laboratories

Use satellite laser-ranging data to estimate precise ephemerides for Lageos, GEOS, and Starlette satellites to study anomalous forces on satellites and definition of the moment-of-inertia reference systems.

E-33 Measurement of Earth Tides at NASA Tracking Stations

William E. Farrell, System, Science and Software

Calculate vertical tidal displacements and accelerations (ocean load tide plus body tide) as a function of time at the various NASA tracking stations, and provide a global Earth tide data base for constructing global models of the principal ocean tide constituents.

E-34 Estimation of Solid Earth/Ocean Tide Parameters from Satellite Tracking

T.L. Felsentreger, NASA, Goddard Space Flight Center

Estimate improved low degree and order ocean/solid Earth tidal parameters for the M_2 and other constituents and the present-day tidal acceleration of the Moon.

E-35 The Value of Q at Tidal Frequencies Obtained from Laser Tracking of Lageos and Other Geodetic Satellites.

Clyde C. Goad, National Oceanic and Atmospheric Administration

Use information on the orbital perturbations of Lageos and other satellites to estimate the "Q" of the solid Earth at tidal frequencies.

E-36 Use of Artificial Satellite Laser Data for Tidal Studies.

Anne Cazenave, Groupe de Recherches de Geodesie Spatiale, Toulouse, France

Apply semi-analytical methods to derive total perturbations for Lageos, GEOS 3 and Starlette orbits obtained from available laser ranging data.

E-37 Advanced Studies for the Geodynamics Program

Ivan I. Mueller, The Ohio State University

Evaluate the geodynamic requirements and the problems encountered when establishing coordinate systems for the non-rigid Earth.

APPENDIX B. CRUSTAL DYNAMICS INVESTIGATIONS

C-1 SAFE II

Christopher H. Scholz, Lamont-Doherty Geological Observatory,
Columbia University

Study movement along the San Andreas Fault to determine how that deformation is distributed.

C-2 Interpretation of Crustal Deformation Data in Southern California

John B. Rundle, Sandia National Laboratories

Analyze southern California crustal deformation using data obtained by VLBI and SLR techniques and from the U.S. Geological Survey.

C-3 Empirical Strain Modeling and Verification of Space Geodetic Information

John L. Fanelow, Jet Propulsion Laboratory

Derive empirical crustal strain models from on-going VLBI observations in California.

C-4 Tectonic Deformation in Southern California

David D. Jackson, Institute of Geophysics and Planetary Physics,
University of California

Study ongoing horizontal tectonic displacements in California using a combination of data from VLBI, SLR and conventional survey techniques of trilateration and triangulation.

C-5 Measurement of Fault Motion in the Western United States.

David E. Smith, Goddard Space Flight Center

Coupled with previous measurements of the San Andreas Fault, this investigation will provide an estimate of the gross motion along the fault to an accuracy of the order of ± 1.5 cm/yr averaged over 8 years.

C-6 Modeling of Tectonophysical Distortion from Measurements of Long-Baseline Geodetic Data and other Geophysical Parameters

James H. Whitcomb, Cooperative Institute for Research in Environmental Sciences, University of Colorado

Construct strain models of the fault system in Southern California using two-dimensional finite element techniques.

C-7 Modeling of Tectonophysical Distortion from Measurements of Long-Baseline Geodetic Data and other Geophysical Parameters

James H. Whitcomb, University of Colorado

Model the tectonic stress-strain rheology of the plate boundary region in the western United States and correlate the long-baseline geodetic data and models with other geophysical parameters in the region.

C-8 Space Based Measurements of Crustal Deformation in the U.S.: Interpretation in Light of Other Geodetic, Geophysical, and Geological Information

Jack Oliver, Cornell University

Use VLBI and laser ranging data together with ground based geodetic measurements to better define contemporary deformation near the active plate boundary in Western U.S. and to define possible internal deformation of the North American continental lithosphere.

C-9 Finite Element Modeling of Crustal Strain

Gregory A. Lyzenga, Jet Propulsion Laboratory

Model the tectonic structure and rheology of the southern California crust and upper mantle using finite elements methods. The same numerical methods will be employed to treat the crustal deformation information made available through VLBI and TIRS observations near other plate boundaries, chiefly from the circum-Pacific belt.

C-10 The Seismotectonics of Plate Boundaries

J. Berger, J.N. Brune, J. Goodkind, F. Wyatt, D.C. Agnew, and C. Beaumont, University of California, Dalhousie University, Canada

Conducted research in both instrument development and observation analysis related to the seismotectonics of Southern California and the Northern Gulf of California.

C-11 Finite Element Studies of the Surface Strain Field Adjacent to the San Andreas Fault

Donald L. Turcotte, Cornell University

Study the scale length of strain accumulation normal to the San Andreas Fault.

C-12 Correlation of Data on Strain Accumulation Adjacent to the San Andreas Fault with Available Models

Donald L. Turcotte, Cornell University

Cyclic accumulation of strain associated with great earthquakes in the San Andreas Fault will be studied using numerical modeling. In addition, the distribution of strain across the Western United States will be studied to determine whether the Eastern United States behaves as a rigid plate.

C-13 Models of Coseismic and Post-Seismic Deformation and Studies of Regional Seismicity

Steven C. Cohen, NASA, Goddard Space Flight Center

Develop a model for post seismic deformation and stressing of the crust and subcrustal layers of the Earth, using viscoelastic relaxation of the lower lithosphere and asthenosphere following an earthquake.

C-14 Finite Element Investigation of Lithosphere Tectonics

H.J. Melosh, State University of New York at Stony Brook

Study coseismic displacements accompanying an earthquake on a long strike slip fault using an elastic screw dislocation model.

C-15 Models for Rupture Mechanics of Plate Boundaries and Crustal Deformation

Amos M. Nur, Stanford University

Develop a general model for the mechanics of plate boundary rupture--including the seismic rupture in its upper part, and the aseismic yielding in the lower part of the lithosphere.

C-16 Testing of Hypotheses in Crustal Dynamics Using VLBI and SLR Data from California

G. Peter Bird, University of California

Analyze and determine the rheology of the crust and upper mantle in California through numerical modeling.

C-17 Towards a Statistical Understanding of Tectonic Motions

Duncan Carr Agnew, Scripps Institution of Oceanography

Apply statistical time series analysis methods to the study of irregularities in regional crustal deformation.

C-18 SLR/VLBI Investigation of Regional Lithospheric Deformation and Contemporary Plate Motions

Seth Stein, Northwestern University

Study regional deformation in the Basin and Range Province by combining SLR/VLBI observations with field geology.

C-19 Late Cenozoic Tectonics of the Basin and Range Province

Paul D. Lowman, Jr., NASA/Goddard Space Flight Center

Use aerial and satellite image data and data from field studies to analyze the Late Cenozoic tectonic setting of the Basin and Range Province.

C-20 Studies of Continental Deformation, Plate Motion and Polar Motion using Geodetic Data from Space Techniques

Richard J. O'Connell, Harvard University

Analyze baseline data and other geophysical measurements to study plate deformation.

C-21 Measurement of Crustal Motion in the United States Using Laser Tracking Observations

Ronald Kolenkiewicz, NASA, Goddard Space Flight Center

Study regional deformation in the Western United States and the relative tectonic plate motion and boundary characteristics of the North American and Pacific plates.

C-22 VLBI Measurements in Alaska to Determine Plate Convergence, Intra-plate Deformation, and Possible Coseismic Displacements

Tracy Johnson, Lamont-Doherty Geological Observatory, Columbia University

Use baseline measurements between sites in Alaska and other locations to determine relative Pacific-North American plate motion and any spatial or temporal variations, study internal deformation in continental Alaska, and possibly measure coseismic deformation during an earthquake.

C-23 Tectonic, Seismic and Geodetic Studies of the Gulf and Peninsula of California

Gordon Ness, Western Oregon State College

Conduct geophysical and geodetic studies of the Gulf of California and adjacent land masses and analyze intersite baseline information

to determine the neotectonic pattern of the Gulf of California fault system.

C-24 North American Plate Deformation in Canada

Anthony Lambert, Dept. of Energy, Mines and Resources, Canada

Study plate deformation between the east and west coasts of Canada; deformation near Alaska; and intercompare Canadian and U.S. VLBI systems.

C-25 Neotectonics of the Northern Caribbean Plate Boundary Zone - A Study in Hispaniola

Kevin Burke, State University of New York at Albany

Photointerpretation and field mapping of Hispaniola will be used to study the nature of continental-style interplate deformation occurring within the North American-Caribbean plate boundary zone.

C-26 Conduct Crustal Dynamics Investigations Along the Eurasian-African Plate Boundary

Peter Wilson, Institut für Angewandte Geodäsie, Federal Republic of Germany

Use laser ranging and VLBI techniques to conduct a detailed investigation of the dynamic changes encountered at the crustal plate boundaries in the Mediterranean.

C-27 Strategies for Satellite Laser Ranging to Investigate Crustal Movements as Related in Particular to the Eurasian Lithospheric Plate

Leendert Aardoom, Delft University of Technology, Netherlands

Conceive, develop, and apply satellite laser ranging strategies, aimed at the establishment of a basic geodetic network to detect and monitor crustal motions in the area selected.

C-28 Displacement, Strain and Relative Plate Motion in the Africa/Arabia/Anatolia/Eurasia Plate System: Synthesis of Landsat and Ground Studies with VLBI Data

John F. Dewey, State University of New York at Albany

Conduct field studies of the North Anatolian and East Anatolian Transform Faults, using Landsat images.

- C-29 Structural and Tectonic Evolution of the North Anatolian Fault: A Pilot Study in Synthetic Integration of Field Investigations and Landsat Interpretation in the Evolution of Intracontinental Plate Boundaries.

John F. Dewey, State University of New York at Albany

Study the North Anatolian transform fault to achieve an understanding of the evolution of the structure and tectonics of intracontinental transform fault systems.

- C-30 Crustal Dynamics of the Eastern Mediterranean

Max Wyss, Cooperative Institute for Research in Environmental Sciences, University of Colorado

Study of the crustal dynamics of the Eastern Mediterranean region using both geodetic measurement and geologic studies.

- C-31 Networks for Earthquake Research

Hans-Gert Kahle, Huebwiessenstrasse, Switzerland

Model earthquake mechanisms associated with the relative plate motions in the zone of contact between the Adriatic promontory and the European foreland using Doppler, SLR, and VLBI measurements.

- C-32 Study of Geophysical Mechanisms of Recent Crustal Movements Affecting Scandinavian Tied Space Geodetic Baselines

Allen Joel Anderson, University of Colorado and the University of Uppsala

Study geophysical mechanisms responsible for spatial variations in precise space geodetic baselines for the Scandinavian Region.

- C-33 Contributions of GRGS to Crustal Dynamics by VLBI Techniques

Claude Boucher, Groupe de Recherches de Geologie Spatiale, France

Equip the EISCAT (European Incoherent Scatterometer) radio observatory in northern Sweden with VLBI equipment and use it in the global program of VLBI observatory operations.

- C-34 Geophysical Study of the Structure and Processes of the Continental Convergence Zones Alpine-Himalayan Belt

M. Nafi Toksoz, Massachusetts Institute of Technology

Perform a detailed geophysical study, using Earth-based and satellite data, of the Alpine-Himalayan belt to aid in the understanding of the processes and consequences of continental collisions.

C-35 Seismicity and Active Tectonics of the Andes and the Origin of the Altiplano

Peter Molnar, Massachusetts Institute of Technology

Study the seismicity and the faulting processes of shallow earthquakes in order to understand how the crust deforms.

C-36 Determination of the Large-Scale Crustal Motion of Australia by Satellite Laser Ranging

Artur Stolz, University of New South Wales, Australia

Evaluate the attainable accuracy of the satellite laser ranging solutions for the relative position of stations, determine the large-scale deformation of the Australian plate, and measure the relative motions of plates in the Australasian region.

C-37 New Zealand/NASA Cooperative Crustal Deformation Program

R. I. Walcott, Geophysics Division, Department of Scientific and Industrial Research, New Zealand

Measure coastal deformation in New Zealand and study the relative movement of the Australian and Pacific plates.

C-38 Plate Motions and Deformations from Geologic and Geodetic Data

J. Bernard Minster and Thomas H. Jordan
Systems, Science, and Software Scripps Institution of Oceanography

Use global plate-motion models to predict the relative motion vectors between proposed project sites and their uncertainties.

C-39 The Interpretation of Crustal Dynamics Data in Terms of Plate Motions and Regional Deformation Near Plate Boundaries

Sean Carl Solomon, Massachusetts Institute of Technology

Interpret data for plate motions between the North American, Eurasian, Pacific, Nazca, and South American plates, and for plate deformation near active margins to determine which parameters are most important in reproducing observed deformation and state of stress.

C-40 Determination of Worldwide Tectonic Plate Motions and Large Scale Intra-Plate Distortions

Peter L. Bender, Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards

Use station positions derived from Lageos ranging and VLBI data to obtain new information on the present rates of worldwide plate tectonic motions and large scale distortions within the plates.

C-41 Intraplate Deformation, Stress in the Lithosphere and the Driving Mechanism for Plate Motions

Bradford H. Hager, California Institute of Technology

Determine large scale intraplate strains from changes in baseline lengths and calculate the state of lithospheric stress using three-dimensional finite element methods.

C-42 VLBI Determination and Interpretation of Relative Motions Within a Network of Sites in North America and Europe

Irwin I. Shapiro, Smithsonian Astrophysical Observatory

Analyze VLBI observations from antennas in North America and Europe to aid in the understanding of forces that govern plate tectonics and to illuminate possible relationships between plate motions and earthquakes.

C-43 A Program in Crustal Dynamic and Earthquake Research

Alfonso Lopez Arroyo, Instituto Geografico Nacional, Spain

Use the Madrid DSN station to observe plate movement and deformation in connection with VLBI observatories in Europe and North America.

C-44 Present Relative Plate Motions of the Nazca and South America Plates and Internal Plate Deformations of the Andean Region

Edgar Kausel, University of Chile, Chile

Study regional deformations and strain accumulations related to large earthquakes along the western coast of South America.

C-45 Determination of the Relative Horizontal and Vertical Motions of Stations in the Laser Tracking Network

David E. Smith, NASA Goddard Space Flight Center

Determine the rates of change of baseline length between all major stations of the laser tracking network, the stability of these rates (data permitting), the stability of the heights of the major laser

stations above a reference surface and the significance of any variations.

C-46 Satellite Laser Ranging Applications to Crustal Dynamics

Bryon D. Tapley, The University of Texas at Austin

Study application of satellite laser ranging to the precise determination of TLRS coordinates, global laser stations network coordinates, global baselines between geodetic markers, polar motion, length of day and UT1.

C-47 Tracking Station Coordinate Determination and Lithospheric Plate Motion Investigation.

Ronald G. Williamson, EG&G/Washington Analytical Services

Precision laser tracking of stable extraterrestrial references (Lageos, Starlette, GEOS 3) will be used to make global measurements of the motion of crustal lithospheric plates, with special emphasis on detecting motion between some of the faster moving plates.

C-48 Determination of Worldwide Mobile Station Positions and Geodynamics Reference System.

Peter L. Bender, National Bureau of Standards

Procedures and algorithms for establishing a world-wide geodynamics reference system will be studied, along with gravity changes at selected sites and correlation of variations with elevation changes.

C-49 Precision and Reliability Station Determination in Selected Areas with a View of Investigating the Potentiality to Detect Relative Station Displacements.

L. Aardoom, Delft University of Technology, Netherlands

Evaluate the precision of laser ranging data and its qualitative effect on the reliability of the outcome of existing reduction models. Provide recommendations for the optimum design of monitoring networks for geodynamic parameter estimation.

C-50 Center of Mass Laser Ranging Station Coordinate Determination and Lithospheric Plate Motion Investigation

James G. Marsh, NASA Goddard Space Flight Center

Determine the center of mass coordinates of global laser ranging stations, and compare results with those obtained by other methods.

C-51 Contribution of Shanghai Observatory to Crustal Dynamics for the Period 1982-1986

Ye Shu-Hua, Shanghai Observatory, Peoples Republic of China

Intercompare VLBI and SLR data collected by NASA and CERTI with Doppler tracking data and classical optical observations to estimate their accuracies, to detect possible systematic errors, and to explore the sources of these errors; analyze variations of short period terms of polar motion and UT1; and evaluate possible correlations between Earth rotation, earthquakes, atmospheric and oceanic circulations, solar bursts and other related phenomena.

C-52 Satellite Laser and VLBI Technique Validation Through Intercomparison of Vector Baselines

James Ryan, NASA, Goddard Space Flight Center

Intercompare laser ranging and VLBI baselines to validate the methods for baseline determination.

C-53 Simultaneous Adjustment of Spatial and Terrestrial Geodetic Data

V. Ashkinaze, University of Nottingham, England

Investigate optimum methods of combining and simultaneously adjusting spatial and terrestrial data to determine the contribution of the various observational techniques to the final accuracies of the baselines between the observing stations.

C-54 Studies of Crustal Movement Measurement Techniques

P.L. Bender and D.R. Larden, Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado

Evaluate and compare methods for measuring crustal movements to understand the various sources of systematic errors which affect the different techniques, and the practical problems involved in using them in the field.

C-55 Measurement of a Baseline to High Precision Using VLBI

K.J. Johnston, Naval Research Laboratory

Use VLBI experiments between Haystack /Westford and Maryland Point Observatory to evaluate methods for determining a baseline to very high precision.

- C-56 Development of Techniques to Reduce the Error in VLBI Determinations of Transcontinental and Intercontinental Baseline Lengths to Less than One Centimeter

Alan E.E. Rogers, Northeast Radio Observatory Corp.

Test an experimental procedure for resolving the X-band phase ambiguity in VLBI and demonstrate the use of phase delay observables to achieve the ultimate limits on accuracy imposed by the atmosphere.

- C-57 Improving the VLBI Reference Frame

David B. Shaffer, Phoenix Corporation

Produce an improved catalog of compact radio sources.

- C-58 GPS Satellite Orbit Determination Using the Reconstructed Carrier Phase Method

Peter L. Bender, Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards

Study the reconstructed carrier phase method to determine geodetic baselines accurately with very short measurement time per site and the GPS satellite orbit determination problem.

- C-59 SERIES-GPS Portable Radio Geodesy

J. Young, D.J. Spitzmesser and L.A. Buennagel, Jet Propulsion Laboratory

Develop the Satellite Emission Range Inferred Earth Surveying (SERIES) receiver which makes use of GPS radio transmissions without knowledge of the coded sequence of transmissions.

- C-60 Very Long Baseline Interferometric Geodesy with GPS Satellites

C.C. Counselman III, Massachusetts Institute of Technology

Develop the use of very long baseline interferometry observations of Earth satellites for determinations of baseline vectors up to several thousand kilometers in length.

- C-61 Utilization of Range and Range Difference Observations in Geodynamics.

Ivan I. Mueller, Ohio State University

Apply range and range difference parameters for the determination of station configurations which are optimal in the geometric sense.

C-62 Australia/NASA Crustal Deformation Program Using VLBI Techniques

Artur Stolz, University of New South Wales, Australia

Perform a pilot experiment to operate various sizes of antennas in order to involve the Australian geodynamics community in VLBI. The desired results are to measure baselines in the range of 300-2500 km between Australian sites to an accuracy of 10 cm.

C-63 Inherent Accuracy of the Water Vapor Radiometry Technique

George M. Resch and R.B. Miller, Jet Propulsion Laboratory

Test water vapor radiometer performance.

C-64 Earth Strain Measurements With the Transportable Laser Ranging System: Field Techniques and Planning.

Yosio Yakamora, University of Texas, Galveston

Study the feasibility at using the TLRS for monitoring local ground deformation around satellite ranging stations and other geodetic control points. Evaluate the usefulness of the relative lateration technique.

C-65 Studies of Atmospheric Refraction Effects on Laser Data.

Peter J. Dunn, EG&G/Washington Analytical Services

Investigate methods of reducing errors in laser ranging data introduced by atmospheric refraction, including improved refraction models, and use of a laser system which transmits light at two different frequencies

C-66 Improvements in Benchmark Stability for Precision Tilt Measurements of Crustal Dynamics

Jonathan Berger and Frank Wyatt, Scripps Institution of Oceanography

Comparing strain measurements with geodetic data in the western U.S. to determine the rheology of the crust as it responds to seismic and tidal influences.

APPENDIX C. GEOPOTENTIAL FIELDS INVESTIGATIONS

G-1 Gravity Field Improvement

Richard H. Rapp, The Ohio State University

Produce a $1^0 \times 1^0$ anomaly field analysis, develop anomaly prediction techniques for 5^0 equal areas, and study the effects of geoid undulations, using Seasat and terrestrial data.

G-2 Gravity Model Improvement for Lageos

Francis J. Lerch, NASA, Goddard Space Flight Center

Develop a refined gravity field model using the Lageos orbital data.

G-3 Gravity Model Improvement Using Laser Data.

W.T. Wells, EG&G/Washington Analytical Services

Use highly accurate laser tracking data for Lageos, Seasat, and other satellites to improve the low degree and order terms of the geopotential models.

G-4 Development of a New British Orbital Analysis Program.

Arthur J. Meadows, University of Leicester, England

Use Lageos data for testing a new orbital analysis program currently under development in England.

G-5 Tentative Determination of General Relativity B Coefficient Using Secular Variations of Perigee of Laser Satellites.

M. Lefebvre, Group de Recherches de Geodesie Spatiale, France

Study laser satellite data and models of all the relevant features of orbit perturbations so as to permit isolation of relativity effects.

G-6 Study of Relativistic Effects on Lageos Orbit Determination and Parameter Estimations.

Chreston F. Martin, EG&G/Washington Analytical Services

Study the effects of using a full general relativistic formulation of the Lageos motion and of the laser ranging measurements.

- G-7 Interpretation and Delineation of the Earth's Gravity Field
Bruce D. Marsh, The Johns Hopkins University
Compare gravity field models and satellite derived geoids and correlating them to major tectonic features of the central Pacific.
- G-8 Development of a Superconducting Tensor Gravity Gradiometer
Ho Jung Paik, University of Maryland
Develop a three-axis superconducting gravity gradiometer.
- G-9 Magnetic Field Measurements and Interpretation
Robert A. Langel, NASA Goddard Space Flight Center
Use Magsat data to derive magnetic field models and to study the spectra of the field to aid in separating core and crustal fields.
- G-10 Spherical Harmonic Representation of the Main Geomagnetic Field for World Charting and Investigation of Some Fundamental Problems of Physics and Geophysics.
David R. Barraclough, Institute of Geological Sciences, United Kingdom
Produce an accurate model of the main geomagnetic field, together with reliable estimates of the accuracy of coefficients.
- G-11 Geomagnetic Field Modeling by Optimal Recursive Filtering.
Bruce P. Gibbs, Business and Technological Systems, Incorporated
Produce a state vector to predict field values for several years beyond the Magsat mode; obtain optimal estimates of field values throughout the 1900-1980 period.
- G-12 Equivalent Source Modeling of the Main Field Using Magsat Data.
Michael A. Mayhew, National Science Foundation
Model the core field; compute equivalent spherical harmonic coefficients for comparison with other field models; examine the spectral content of the core field.
- G-13 Study of Enhanced Errors and of the Secular Magnetic Variation Using Magsat Models and Those Derived in POGO Surveys.
David P. Stern, NASA/Goddard Space Flight Center
Estimate the secular variation over the period 1965-80 by removing mathematical instability based upon scalar field intensity alone.

G-14 Improved Definition of Crustal Magnetic Anomalies in Magsat Data.

Robert D. Regan, Aero Services, Incorporated

Develop an improved method for the identification of magnetic anomalies of crustal origin in satellite data by defining and removing the most persistent external field effects.

G-15 A Proposal for the Investigation of Magsat and Triad Magnetometer Data to Provide Corrective Information on High-Latitude External Fields.

Thomas A. Potemra, The Johns Hopkins University Applied Physics Laboratory

Identify and evaluate high-latitude external fields from the comparison of data acquired by the Magsat and Triad spacecraft that can be used to improve geomagnetic field models.

G-16 Investigation of the Effects of External Current Systems on the Magsat Data Utilizing Grid Cell Modeling Techniques.

David M. Klumpp, The University of Texas at Dallas

Apply a modeling procedure to the vector Magsat data in order to separate the terrestrial component from that due to extraterrestrial sources.

G-17 Studies of High-Latitude Current Systems Using Magsat Vector Data.

J. Ronald Burrows, National Research Council of Canada

Understand the physical processes that control the high-latitude current systems; improve the confidence level in studies of internal field sources.

G-18 The Reduction, Verification and Interpretation of Magsat Magnetic Data over Canada.

Richard L. Coles, Energy, Mines and Resources, Canada

Select quiet-time data; correct Magsat data for disturbance fields and apply the routines; compare Magsat and vector airborne data; combine Magsat and aircraft data of magnetic anomalies; produce regional interpretations relating to earth structure.

G-19 Compatibility Study of the Magsat Data and Aeromagnetic Data in the Eastern Piedmont of the U.S.

Ihn Jae Won, North Carolina State University

Evaluate the compatibility between the Magsat and aeromagnetic data in the eastern North Carolina Piedmont.

G-20 Magsat Anomaly Field Inversion and Interpretation for the U.S.

Michael A. Mayhew, National Science Foundation

Construct a regional crustal temperature/heat flow model based on a developed magnetization model, heat flow/production data, and spectral estimates of the Curie depth.

G-21 Use of Magsat Anomaly Data for Crustal Structure and Mineral Resources in the U.S. Midcontinent.

Robert S. Carmichael, University of Iowa

Analyze Magsat anomaly data to synthesize a total geologic model and interpret crustal geology in the midcontinent region; contribute to the interpretation and calculation of the depth of the Curie isotherm.

G-22 Identification of the Magnetic Signatures of Lithostratigraphic and Structural Elements in the Canadian Shield Using Magnetic Anomalies and Data from Individual Tracks from Magsat.

D.H. Hall, University of Manitoba, Canada

Confirm and extend the model for crust mantle magnetization.

G-23 Proposal to Analyze the Magnetic Anomaly Maps from Magsat over Portions of the Canadian and Other Shields.

David W. Strangway, University of Toronto, Canada

Examine the expected difference between the Grenville and Superior provinces.

G-24 Herbert V. Frey, NASA, Goddard Space Flight Center

Satellite Geopotential Anomalies: Global Distribution and Relation to Surface Data

Study broadscale anomalies, using improved gravity models and Magsat magnetic anomaly data, and the significance of their distribution across the globe through qualitative comparison with three other global data sets.

G-25 The Mineralogy of Global Magnetic Anomalies.

Stephen E. Haggerty, University of Massachusetts

Interpret Magsat data to locate mafic and ultramafic source rocks and lineament expressions of anomalies that can be correlated with crustal or upper mantle depths; determine mineral stabilities pertinent to magnetic anomalies to ascertain the magnetic properties of metamorphic rocks.

- G-26 Magsat Data, the Regional Magnetic Field, and the Crustal Structure of Australia and Antarctica.

James C. Dooley, Bureau of Mineral Resources, Australia

Incorporate Magsat data into regional magnetic field charts to improve their accuracy; determine if differences exist in temperature-depth curves for different tectonic areas; study the boundaries between major tectonic blocks and between continental and oceanic crust; determine Curie point depth and crustal magnetization for Antarctica.

- G-27 Investigation of Antarctic Crust and Upper Mantle Using Magsat and Other Geophysical Data.

Charles R. Bentley, University of Wisconsin

Using Magsat data, devise a general framework for the structure of Antarctica into which more specific and local measurements can be integrated.

- G-28 An Investigation of the Crustal Properties of Australia and Surrounding Regions Derived from Interpretation of Magsat Anomaly Field Data.

B. David Johnson, Macquarie University, Australia

Produce a map of surface magnetization to understand the evolution of the crust and to aid in mineral exploration.

- G-29 Application of Magsat to Lithospheric Modeling in South America: Part I - Processing and Interpretation of Magnetic and Gravity Anomaly Data.

William J. Hinze, Purdue University

Use magnetic anomalies to develop lithospheric models to determine the properties of principal tectonic features; correlate magnetic anomalies of South America with those of adjacent continental areas to attempt to reconstruct Gondwanaland (see Keller below).

- G-30 Application of Magsat to Lithospheric Modeling in South America: Part II - Synthesis of Geologic and Seismic Data for Development of Integrated Crustal Models.

G.R. Keller, The University of Texas at El Paso

Provide models of the seismic velocity structure of the lithosphere (see Hinze above).

G-31 Structure, Composition, and Thermal State of the Crust in Brazil.

Igor I. Gil Pacca, Instituto Astronomico e Geofisico -- Brazil

Construct preliminary crustal models in the Brazilian territory; point out possible variations in crustal structure among different geological provinces.

G-32 An Investigation of Magsat and Complementary Data Emphasizing Precambrian Shields and Adjacent Areas of West Africa and South America.

David A. Hastings, U.S. Geological Survey, EROS Data Center

Determine the Magsat magnetic signatures; synthesize Magsat and other data with mineral resources data globally.

G-33 Magnetic Anomaly of Bangui.

M.R. Godivier, Office de la Recherche Scientifique et Technique, Outremer, France

Improve the explanation of the cause of the Bangui anomaly, using Magsat data, other magnetic data, and gravity, seismic, and heat flow data.

G-34 Magsat Investigations Consortium.

Jean-Louis LeMouel, Institut de Physique du Globe de Paris, France

Reduce Magsat vector data for a global analytic field model and constant altitude field maps; compare Magsat data to regional studies; study features of the core field; correlate globally and regionally Magsat and gravimetric data.

G-35 Crustal Structures under the Active Volcanic Areas of Central and Eastern Mediterranean.

Paolo Gasparini, Osservatorio Vesuviano, Italy

Calculate the depth of the Curie temperature for the Mediterranean area and relate to areas of volcanic activity; investigate the Italian and Tyrrhenian anomaly.

G-36 The Age of Satellite-Observed Magnetic and Gravity Anomalies Using Paleo-Reconstructions

Herbert V. Frey, NASA, Goddard Space Flight Center

Examine the patterns of broadscale magnetic and gravity anomalies as they might have existed in the early Mesozoic era, before the breakup of Pangaea.

- G-37 Analysis of Intermediate-Wavelength Magnetic Anomalies over the Oceans in Magsat and Sea Surface Data.

John L. LaBrecque, Lamont-Doherty Geological Observatory

Determine the distribution of intermediate wavelength magnetic anomalies of lithospheric origin in the oceans, the extent to which Magsat describes the distribution, and the cause of these anomalies.

- G-38 Investigations of Medium Wavelength Magnetic Anomalies in the Eastern Pacific Using Magsat Data.

Christopher G.A. Harrison, University of Miami

Determine the relationship of magnetic anomalies with surface geological features.

- G-39 Japanese National Team for Magsat Project.

Naoshi Fukushima, Geophysics Research Laboratory, Japan

Analyze the regional geomagnetic field around Japan and Japanese Antarctica; study the contributions to magnetic variations by electric currents and hydromagnetic waves in and above the ionosphere.

- G-40 Magsat for Geomagnetic Studies in the Indian Region.

B.N. Bhargava, Indian Institute for Geomagnetism

Prepare a regional geomagnetic reference field and magnetic anomaly maps over Indian and neighboring regions: (a) to gain a clearer understanding of secondary effect features and the variability of the dawn/dusk field, and (b) to study in detail the equatorial electrojet and transient variations.

- G-41 Satellite Magnetic and Gravity Investigation of the Eastern Indian Ocean.

Robert F. Brammer, The Analytic Sciences Corporation

Produce magnetic anomaly maps of the Indian Ocean; quantify the comparison between Magsat data and GEOS 3 gravity data; interpret the magnetic data using ancillary data.

- G-42 Geomagnetic Field Forecasting and Fluid Dynamics of the Core.

Edward R. Benton, University of Colorado

Adjust the gauss coefficients of the main field model of the Magsat data set to satisfy dynamic constraints; use Magsat data to test the ability to forecast the structure of the internal geomagnetic field.